2021-06

ANALYSIS ON HOW THE MARINE CORPS HAS CREATED POLICY AND INTEGRATED ADDITIVE MANUFACTURING THROUGHOUT THE FORCE

Norako, Vincent R.

Monterey, CA; Naval Postgraduate School

http://hdl.handle.net/10945/67790

NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

JOINT APPLIED PROJECT REPORT

ANALYSIS ON HOW THE MARINE CORPS HAS CREATED POLICY AND INTEGRATED ADDITIVE MANUFACTURING THROUGHOUT THE FORCE

June 2021

By: **Vincent R. Norako**

Advisor: **Brad R. Naegle**
Co-Advisor: **Bryan J. Hudgens**

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REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2021	**3. REPORT TYPE AND DATES COVERED** Joint Applied Project Report	
4. TITLE AND SUBTITLE ANALYSIS ON HOW THE MARINE CORPS HAS CREATED POLICY AND INTEGRATED ADDITIVE MANUFACTURING THROUGHOUT THE FORCE			**5. FUNDING NUMBERS**
6. AUTHOR(S) Vincent R. Norako			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This joint applied project analyzed the Marine Corps' integration of additive manufacturing (AM) technology throughout the force. Principally, it analyzed the publication Marine Corps Order (MCO) 4700.4 and examined how this document supports AM integration. The primary research question addressed AM's current position within the Marine Corps and what areas could be improved. The most significant area for improvement was cybersecurity concerns. One secondary research question addressed specific risks AM technologies present and how the Marine Corps has or can mitigate those risks. This question supported the primary research question by expounding on the risks of cybersecurity to AM. Another secondary research question was to address what unique opportunities AM technologies provide and how the Marine Corps can fully harness those opportunities. This research question demonstrated AM's benefits beyond maintenance and cost savings, such as humanitarian aid and disaster relief operations and logistics operations within China's weapon engagement zone in the South China Sea. Overall, this analysis sought to provide direction and focus to any potential revision of MCO 4700.4 in the future. The data collection was conducted by examining recent articles (approximately less than five years) to determine the state of the technology in the private, public, and military sectors. The analysis remained at the unclassified level to ease distribution of this report.

14. SUBJECT TERMS Marine Corps, Marine Corps Order, MCO, additive manufacturing, AM, 3D printing, programmatic approach			**15. NUMBER OF PAGES** 93
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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Vincent R. Norako, Major, United States Marine Corps

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PROGRAM MANAGEMENT

from the

NAVAL POSTGRADUATE SCHOOL
June 2021

Approved by: Brad R. Naegle
Advisor

Bryan J. Hudgens
Co-Advisor

Raymond D. Jones
Academic Associate, Graduate School of Defense Management

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
3DP	three-dimensional printing
ACES	Automated Construction of Expeditionary Structures
AM	additive manufacturing
AMOS	additional military occupational specialty
ATO	authority to operate
BOD	building on demand
CAC	Common Access Card
CAD	computer aided design
CIA	confidentiality, integrity, and availability
CNC	computerized numerical controlled
CSAM	construction scale additive manufacturing
DC AVN	Deputy Commandant for Aviation
DC CD&I	Deputy Commandant, Combat Development and Integration
DC I	Deputy Commandant, Information
DC I&L	Deputy Commandant, Installation and Logistics
DLA	Defense Logistics Agency
DMDV	Digital Manufacturing Data Vault
DOC	Department of Commerce
DOD	Department of Defense
DODIG	Department of Defense Inspector General
DON	Department of the Navy
FFF	Fused Filament Fabrication
FIPS	Federal Information Processing Standards
FY	fiscal year
GAO	Government Accountability Office
GCSS–MC	Global Combat Support System–Marine Corps
GSE	ground support equipment
ICRC	International Committee of the Red Cross and Red Crescent
IEP	information exchange portal

IMA	Intermediate Maintenance Activities
I&L	Installation and Logistics
IP	intellectual property
IRBM	intermediate-range ballistic missile
JAMMEX	Joint Additive Manufacturing Model Exchange
JAMSG	Joint Additive Manufacturing Steering Group
JAMWG	Joint Additive Manufacturing Working Group
JTDI	Joint Technical Data Integration
LOE	lines of effort
LOGCOM	Marine Corps Logistics Command
MARADMIN	Marine administrative messages
MCDP	Marine Corps doctrinal publication
MCEN	Marine Corps Enterprise Network
MCICOM	Marine Corps Installations Command
MCO	Marine Corps order
MCSC	Marine Corps Systems Command
MEU	Marine expeditionary unit
MFD	multi-function device
MIBP	Manufacturing and Industrial Base Policy
MOS	military occupational specialty
MOU	memorandum of understanding
MPSRON	maritime pre-positioning ship squadrons
MRBM	medium-range ballistic missile
NATO	North Atlantic Treaty Organization
NAVAIR	Naval Air Systems Command
NDAA	National Defense Authorization Act
NDS	National Defense Strategy
NexLog–AM	Next Generation Logistics–Additive Manufacturing
NIST	National Institute of Standards and Technology
OEM	original equipment manufacturer
OPORD	operation order
PCB	printed circuit boards

POL	petroleum, oils, lubricants
POR	program of record
RMF	Risk Management Framework
ROMO	range of military operations
SLOC	supply line of communication
SOP	standard operating procedure
SIM	subscriber identity module
SMEAC	situation, mission, execution, administration and logistics, command and signal
SP	Special Publication
SRBM	short-range ballistic missile
STL	stereolithography
TACFAB	tactical fabrication
TDP	technical data package
TE	tables of equipment
TECOM	Training and Education Command
TFSMS	Total Force Structure Management System
UAS	unmanned aircraft system
URL	uniform resource locator
USAF	United States Air Force
USD(A&S)	Under Secretary of Defense for Acquisition and Sustainment
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
USD(R&E)	Under Secretary of Defense for Research and Engineering
USMC	United States Marine Corps
USN	United States Navy
WEZ	weapon engagement zone
XFAB	expeditionary fabrication

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ACKNOWLEDGMENTS

First, I would like to thank both of my advisors, Prof. Brad Naegle and Prof. Bryan Hudgens, for their guidance and mentorship throughout this process, which greatly enhanced not only my writing but researching skills. Second, I would like to thank my amazing son, Vincent Roland Norako Jr., who is an inspiration for me to be not only a better father but a better Marine. Finally, I would like to thank my incredible wife, Elise Norako. She is an amazing mother and wife who gave me unwavering love and support throughout this program.

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I. INTRODUCTION

With unhindered supply lines of communications (SLOCs), the U.S. military presents an existential threat to any adversarial nation or nonstate actor. Several historical examples demonstrate how unfettered supply lines provide an overwhelming advantage for an army. One such example is the nomadic Mongolian Horde led by Genghis Khan, who were able to conduct operations far from Mongolia without the hindrance of supply line interference. As a nomadic tribe who roamed and lived off the land, his forces did not require the traditional supply lines back to a rearward base when other armies of the time required this reach back for supplies. Along with a few other factors, this aspect of the Mongolian Horde presented an existential threat to the vastly larger armies of Asia and Eastern Europe (Carlin, 2012).

However, once those SLOCs become threatened, then the existential threat that a dominant nation can impose upon an adversary becomes either significantly degraded or lost entirely. Thus, for the United States to maintain a military advantage over its adversaries, the military must harden these SLOCs for any potential future conflict with near peer adversaries. More specifically, the U.S. military's dominance in the air, land, and sea domains of warfare enables this overmatch against its adversaries. New challenges have arisen with the advent of the space and cyber domain. These new challenges offer gaps for foreign adversaries to exploit and threaten the U.S. military's unhindered SLOCs. Unless steps are taken to harden these SLOCs, the U.S. military will start to face an existential threat instead of being the threat to adversarial state and nonstate actors.

One of the primary missions of the United States Marine Corps (USMC) is to provide the U.S. military with a fighting force that specializes in conducting the full range of military operations (ROMO) in often remote and austere environments. Over the past two decades, the Marine Corps has proven to be successful with the luxury of unhindered SLOCs as the adversaries seen in Iraqi and Afghanistan did not present a significant threat to supplies lines out of the respective country. Unfortunately, the Marine Corps will be severely impacted if those SLOCs were to be hindered. Thus, the Marine Corps must seek out options to either harden or remove the need for these SLOCs.

Additive manufacturing (AM)—or three-dimensional printing (3DP)—provides the Marine Corps an option for hardening and, in certain cases, removing the threat to its SLOCs (note that the terms *AM* and *3DP* are used interchangeably throughout this research). The commercial use of AM started as far back as 1987 with the introduction of stereolithography (STL) but grew rapidly in both reach, availability, and even purpose in the 2010s (Wohlers & Gornet, 2016). Seeing the benefits of AM, the Marine Corps has taken strides over the past decade to integrate AM throughout the force.

The reason why AM is such an enabler for hardening SLOCs is that it allows for the transport of basic manufacturing feedstock such as plastics and metals instead of high-end, low-density end-items such as specialized repair parts through a supply chain. For example, a chassis for a radio system or a plastic handle for a vehicle door could be made from the same polymer. Without AM, the chassis and the door handle would have to be made by specialized and separate vendors and then shipped from, most likely, the continental United States to a foreign and remote location. However, AM offers the sourcing of polymers from both in and out of the continental United States as well as from just one vendor. By requiring transport for only basic manufacturing feedstock and then manufacturing the end-item at the point of need instead of transporting the end-item through the entire supply chain, the Marine Corps can develop multiple SLOCs throughout the world to transport the basic manufacturing feedstock shorter distances and at greater numbers compared to transporting the end-item from the original equipment manufacturer (OEM). The reason for greater numbers is that basic manufacturing feedstock of just polymers offers the warfighter a wider range of end-items as opposed to an end-item that cannot be remade into another part based upon demand. Furthermore, as these OEMs are generally located in the continental United States, a limited number of SLOCs are available. Thus, if the Marine Corps could globalize its SLOCs, they would become hardened through obscurity in the form of various options to draw resources as well as shorter distances from the resource deposit to the point of need.

A. PURPOSE AND BENEFIT OF THIS RESEARCH

This research seeks to evaluate the Marines Corps' efforts in the field of AM. The primary research question is

- What is additive manufacturing's current position within the Marine Corps, and what areas could be improved?

This primary research question does not suggest that great feats have not already been achieved. Furthermore, this research highlights areas where the Marine Corps has excelled, but this primary research question seeks to identify gaps as well to further advance AM in the Marine Corps and harden those gains already achieved. Two secondary research questions address the impacts that AM will have on the Marine Corps in the coming decade:

- What unique risks does AM present to the Marine Corps?
- What specific opportunities does AM provide the Marine Corps that they are not pursuing or are not pursuing to their fullest extent?

As AM has doctrinal implications to how the Marine Corps will supply and sustain future wars, the Marine Corps must take a programmatic approach to AM integration. Scholars and historians state that the world is entering into the Fourth Industrial Revolution with the advent of certain technological advances, including AM, ushering in this revolution. By their very nature, revolutions are highly volatile, and uncertain outcomes are the norm. These new technologies will enable even smaller militaries to be capable of more significant global impacts (Tuang, 2018). If smaller militaries are now able to enter and compete in the global arena, then near peer adversaries could pose significant threats to the U.S. military. Consequently, the Marine Corps must quickly but effectively integrate these new technologies before adversaries can leverage the processes. Without integrating AM correctly, the Marine Corps would allow the United States' adversaries the option to dictate tempo. Thus, the desired benefits of this research are the inclusion or at least consideration of the author's recommendations into any revisions of Marine Corps Order (MCO) 4700.4 or any other AM policy published by the Marine Corps.

B. METHOD

On March 23, 2020, Lieutenant General Charles G. Chiarotti signed MCO 4700.4. This order, the Marine Corps' AM policy, was the first time the Marine Corps dedicated an order to AM. At the time of signing, LtGen Chiarotti was serving as the deputy commandant for installations and logistics. This research centers around evaluating MCO 4700.4, as this document now serves as the source point for all matters pertaining to AM. The research provides an overview of the sections of the order that have done or will do well for the Marine Corps and the parts that either need improvement or inclusion in the revision of the order. Analysis of the order is conducted on pertinent literature in an effort to draw conclusions between the material reviewed and how it has or can positively affect MCO 4700.4.

C. RESEARCH STRUCTURE

This research is structured into five chapters. This first chapter serves as an introduction to the adoption of AM into the Marine Corps. The second chapter provides a background to AM efforts in the Marine Corps and particularly focuses on the published literature prior to the publication of MCO 4700.4. The third chapter is a literature review of civilian and international AM initiatives, Department of Defense (DOD) and Department of the Navy (DON) initiatives, and Marine Corps initiatives outside of the MCO; this chapter concludes with a review of the MCO 4700.4. The fourth chapter will provide an analytical review of and conclusions from the aforementioned literature. The fifth and final chapter provides the author's recommendations as well as suggestions for further research.

II. ADDITIVE MANUFACTURING BACKGROUND IN THE MARINE CORPS

In September 2019, Captain Ian Carter, USMC (2019) wrote a thesis titled "A Systems Approach to Additive Manufacturing in the Marine Corps." In his thesis, Carter captured the then-current status of AM in the Marine Corps and offered a way forward for the Marine Corps to adequately integrate AM throughout the force. His introduction summarizes the several other theses that have been written by fellow Marine Corps officers about AM in the Marine Corps in the past 5 years. He goes on to briefly discuss two Marine administrative messages (MARADMINs) that provided guidance to the Marine Corps for the implementation of AM throughout the force (Carter, 2019). However, at the time of his writing, two more MARADMINs and MCO 4700.4 had not been published yet. This thesis lays out a brief description of each of the MARADMINs to provide context regarding their influence on the MCO and the current status of AM integration in the Marine Corps.

A. MARADMIN 489/16

MARADMIN 489/16 was the initial MARADMIN providing guidance to the Marine Corps on the application of AM. Published in September 2016, MARADMIN 489/16 was not the first time the Marine Corps employed AM; however, it was the first step to formalize AM in the Marine Corps. It defined AM as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive (traditional) manufacturing methodologies" (United States Marine Corps [USMC], 2016, para. 2). Also, it listed the basic materials (plastics, metals, rubbers, energetics, concretes, foods, and organic tissues) and purposes (prototyping, tooling, repair, and manufacturing) of AM in the Marine Corps. The message highlighted that it would only address ground support and would not apply to aviation or ground support equipment (GSE) in support of aviation activities. MARADMIN 209/18 eventually provided that AM aviation guidance, which is discussed in a later section. The message also stressed the highly uncertain and rapidly evolving nature of AM; however, it did not mention anything about cybersecurity considerations.

The major purpose of the MARADMIN was a call for action for commanders to encourage their Marines to seek out innovative solutions while remembering safety, warranty, and intellectual property (IP) considerations (USMC, 2016). The aforementioned solutions being sought were not solely from a maintenance perspective but rather with consideration for overall readiness to study whether AM could not only repair broken parts faster or cheaper, but to allow parts to be remade to be lighter, stronger, or better for the situation at hand. Finally, the MARADMIN designated the deputy commandant of installation and logistics (DC I&L) to serve as the head for AM activities, with the Next Generation Logistics–Additive Manufacturing (NexLog–AM) organization as the lead agent (USMC, 2016).

B. MARADMIN 594/17

Following MARADMIN 489/17, MARADMIN 594/17 was published a year later and provided more clarifying guidance in support of the initial MARADMIN. It specifically targeted commands and commanders at the rank of O-5 or above to be the driving force for a bottom-up approach to the adoption of AM. However, it did not remove innovative latitude that all Marines were to seek out unique solutions to then be submitted up the chain of command. The message also allowed commanders the ability to purchase commercial 3-dimensional (3D) printers and other AM equipment and provided guidance on how to manage and track equipment in the supply system through the Global Combat Support System–Marine Corps (GCSS–MC). The message expanded upon legal considerations and ensured O-5 commanders were informed on IP matters and provided the MCSC patent attorney as a resource for consultation. Finally, this MARADMIN did address cybersecurity but simply tasked MCSC to "develop a plan for the digital repository to safeguard model and data integrity and implement cybersecurity measures" (USMC, 2017, para. 3). Furthermore, it published the uniform resource locator (URL) of the digital repository. Last, all MARADMINs are open-source pieces of information that require zero authentication to access; a simple search through Google could find the MARADMINs archive, MARADMIN 594/17, and the specific URL for the digital repository.

A major contribution of the message came in the form of categorizing AM files into digital bins of green, yellow, and red. Green items were those items either already located in the digital repository of AM parts called the Marine Corps AM Information Exchange Portal (IEP) or that met the risk guidelines of a green category item. The AM IEP was maintained and operated by Marine Corps Systems Command (MCSC). If the item was not located in the digital repository, commands were directed to send their files to MCSC to upload the file to the digital repository. The key distinction of a green item is that it did not require prior approval before printing and applying the item. Yellow items were those not located in the Marine Corps AM IEP and required the approval of the first O-5 in the chain of command due to the item's risk rating. Following the commander's approval, the item's file would be again sent off to MCSC for further review and evaluation prior to inclusion into the digital repository and Marine Corps–wide usage. The red bin category was for those items deemed to present critical or serious risk and required prior approval directly from MCSC prior to printing and usage. However, the message did provide the caveat that if the local O-5 commander deemed that "successful completion of combat operations are at risk" (USMC, 2017) without the item, the item could be printed in those special situations. The takeaway of this green, yellow, and red bin system is that the Marine Corps wanted to empower O-5 commanders and commands into pushing AM integration forward and embracing the bottom-up approach.

Finally, the message introduced the concept of the Marine Maker laboratories on major Marine Corps installations. These spaces would provide Marines of all ranks a facility or workspace with which to collaborate on joint AM projects or endeavors. The primary objective of these laboratories was to "foster creativity, collaboration, risk tolerance, and bottom-up adoption of digital manufacturing techniques" (USMC, 2017).

C. MARADMIN 209/18

Neither MARADMIN 489/16 nor MARADMIN 594/17 provide specific AM guidance regarding aviation equipment. MARADMIN 209/18, published in April 2018, seeks to provide that tailored guidance on the implementation of AM regarding aviation equipment and its GSE. One key point provided by this MARADMIN is that DC I&L

would not be the lead for aviation-specific AM parts; rather, deputy commandant for aviation (DC AVN) would serve as the lead. Furthermore, aviation-specific AM files would need to be routed up to Naval Air Systems Command (NAVAIR) for approval rather than to MCSC. MCSC and NexLog–AM would serve only as a supporting element to aviation AM endeavors. Cases for and against the separation of aviation from the rest of the AM community can be made; however, that argument and research can be addressed in a separate thesis. This research examines AM through a holistic lens and addresses AM activities with the primary focus and research data coming from ground-specific items. However, when aviation-specific items arise, those particulars will be addressed.

D. MARADMIN 055/19

MARADMIN 055/19 serves as the last in a series of MARADMINs to address AM prior to the formal publication of the MCO. Neither this MARADMIN nor any other seeks to be a replacement of the preceding MARADMINs but rather an expansion, and it states that fact in the message's opening statements. As 3 years passed between the original message and this message, MARADMIN 055/19 was able to draw on some data points to highlight the then current status of AM in the Marine Corps. Some of these data points include the number of printers deployed, how many files have been uploaded to MCSC's AM IEP, the introduction of metal AM printers aboard a few major Marine Corps installations and commands, the 3DP of concrete using construction-scale additive manufacturing (CSAM), and the introduction of the first AM program of record (POR)—the expeditionary fabrication (XFAB) container.

Furthermore, the message established the Additive Manufacturing Operations Cell (AMOC) under the command of MCSC. This cell would serve as a "24/7 help desk to answer questions, field requests for prints, and fully vet any part that requires fabrication by a Marine organization" (USMC, 2017). The message also created another working group to work with the United States Navy (USN) and America Makes to formalize a training program.

The message highlighted joint considerations for the first time and implied a few more cybersecurity considerations. However, as the DOD conducts more joint operations and the cyber domain continues to grow in scope and reach, the Marine Corps must take a larger role in developing joint operating procedures and consider cybersecurity vulnerabilities with regard to AM.

E. MCO 4700.4

As stated previously, MCO 4700.4 was signed on March 23, 2020. The order was signed by DC I&L and stated that they would be the lead for AM integration throughout the Marine Corps. However, significant collaboration occurred in the genesis of this order as it affects many different organizations throughout the Marine Corps. One such example is Training & Education Command (TECOM), which plays a significant role in the creation of a training program for AM in the various school houses. Another significant contributor was the MCSC's AMOC. At this point in AM's history in the Marine Corps, the NexLog–AM organization had been replaced by the AMOC as the lead agent of AM integration.

On May 15, 2020, the three ground-specific MARADMINs (i.e., 489/16, 594/17, and 055/19) were canceled, while MARADMIN 209/18 remains active. The reason for this distinction is that MCO 4700.4 as well as MARADMIN 489/16, 594/17, and 055/19 were all signed by DC I&L. MARADMIN 209/18 was signed by DC AVN. MCO 4700.4 even tasks DC AVN to address all aviation-specific AM considerations. The key point to take away is that a clear divide is now formed between aviation and ground AM efforts. The cancellations do not suggest that their material is now invalid; rather, the cancellation marked a strategic shift for AM to become more formalized throughout the Marine Corps by making it an order. The only step remaining to make AM even more formal would be to make AM doctrine. However, that seems unlikely and not entirely necessary—at least at this present time. Marine Corps Doctrinal Publication (MCDP) 4, *Logistics*, could be revised to include AM, but making a stand-alone doctrinal publication just for AM appears unnecessary. Thus, an order is the appropriate level for AM going forward. The two following chapters include a review and analysis of this MCO in context of the current state of AM in the Marine Corps and DOD.

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III. LITERATURE REVIEW

Concurrently to the writing of MARADMINs 489/16, 594/17, 209/18, and 055/19, the civilian sector, the DOD, and other services of the military were planning and implementing AM technology into their respective organizations. As AM provides a strategic shift in several logistics functions, the Marine Corps has and should continue to research these successes and failures to incorporate those lessons into any future revision of MCO 4700.4. This chapter includes a review of civilian and international literature, DOD literature, other military services' literature, and Marine Corps literature outside MCO 4700.4. Following these subsections, this chapter concludes with a comprehensive literature review of MCO 4700.4. Note that all literature is either open-source information and obtained through internet search engines or provided directly from MCSC's AMOC.

A. CIVILIAN AND INTERNATIONAL AM LITERATURE REVIEW

Tuang (2018) wrote that "with the 21st century, we are now witnessing the dawn of the [Fourth Industrial Revolution]" (p. 1). Tuang's research focused on a core group of technologies that were leading this fourth industrial revolution. These technologies include mobile internet through smartphones, integrated and networked sensors, genetic engineering, renewable energy, and AM. All these technologies paired together will allow militaries of all sizes to be "more mobile, less tethered to supply lines, and possess greater operational endurance" (Tuang, 2018, p. 16). Even though AM is only one of these technologies, it will allow the Marine Corps to increase its expeditionary capabilities and maneuver warfare ethos in both kinetic and nonkinetic operations. Kinetic operations relate to combat; an example of a nonkinetic operation is humanitarian assistance and disaster relief (HADR) operations. With applications of AM expanding in scope, the materials being used are also expanding beyond traditional polymers and metals into other materials such as concrete (Hanna, 2019) and circuitry (Elinoff, 2020). AM's use for concrete demonstrates its ability to contribute to large-scale construction of structures and similar-sized items, while its use for the production of circuity demonstrates the expanding list of highly specialized and technical items available for print. However, this industrial revolution is a global phenomenon and is not just isolated to the United States. Thus, any organization must take into consideration the cybersecurity risks and interference from foreign agents when integrating AM technology into their standard operating procedures (SOPs). However, not all foreign agents have nefarious intent toward the United States. The Marine Corps has the opportunity to help allies expand their own AM technologies, partner with allied nations on future AM initiatives, and safeguard U.S. and foreign nations' digital repositories against foreign adversaries seeking attack vectors into this new industrial revolution.

Super Typhoon Yolanda made landfall in the Philippines on November 8, 2013. This Category 5 typhoon significantly damaged several cities and towns throughout the Philippines, including Tacloban City, and dislocated 17 million people from their homes. This storm is considered one of the most powerful typhoons in recorded history (Reid, 2018). The Marine Corps responded swiftly to this humanitarian crisis by conducting Operation Damayan on November 10, 2013 (Lewis, 2013). The Marine Corps sent 250 personnel to deliver 129,000 pounds of relief supplies including food, water, and other emergency supplies. The Marine Corps conducted the emergency evacuations for over 160 individuals in Tacloban City alone. This example is not an isolated incident. From 1990 to 2013, the Marine Corps has conducted over 40 HADR operations for just the Philippines and will continue to do so as disasters occur in that country (Lewis, 2013). Furthermore, the Marine Corps conducts HADR missions not just in the Philippines or the U.S. Indo-Pacific Command (INDOPACOM) area of responsibility (AOR) but around the world. A key enabler for diplomatic relationships with allies and partners is the U.S. capabilities to respond rapidly to disasters.

In 2018, a team of international researchers wrote on the benefits of AM in support of HADR operations and how AM can overcome the unique challenges in HADR operations. First, "Supply chain logistics for humanitarian responses are some of the most complex that exist. It is challenging to forecast both the demand (due to difficulties in knowing both the timing of a disaster and details of the population affected) and the supply" (Savonen et al., 2018, p. 2). Second, with the uncertainty of the location of the disaster and both materials required and availability, 60% to 80% of all aid money is spent on procurement (Savonen et al., 2018). Third, the researchers also highlighted that the International Committee of the Red Cross and Red Crescent (ICRC) has a catalog of approximately 10,000 different items that are shipped to disaster relief locations. The researchers then discussed six 3D printers' requirements and eight design considerations for the ideal printer in HADR operations. Finally, the research concluded with a review and analysis of a 3D printer, the Kijenzi 3D Printer, as one example of a highly mobile and low-profile printer that could have a significant impact on HADR operations.

Savonen and his team's (2018) 3D printer requirements, as seen in Table 1, and design characteristics, as seen in Table 2, offer a grading rubric with which the Marine Corps can assess the 3D printers it plans to use to conduct HADR operations. Even though the ICRC and other civilian entities have different missions during HADR operations, the logistical challenges that both organizations face are similar, and AM can help mitigate those challenges. Unlike other civil–military operations, where host nation support to the military can be expected, disaster operations should employ systems that strive to diminish the demand on host nation assistance to disaster relief operations. Another challenge is that HADR operations require various items to be procured outside the host nation, transported, and then distributed within the host nation.

Table 1. Six Required Capabilities of a Humanitarian 3D Printer. Source: Savonen et al. (2018).

Requirement Number	Requirement Description
Requirement #1	The 3D printer must be able to make useful parts.
Requirement #2	The 3D printer must be able to function independent of infrastructure.
Requirement #3	The 3D printer must be able to be easily transported.
Requirement #4	The 3D printer must be safe and easy to use.
Requirement #5	The 3D printer must be able to withstand harsh environments.
Requirement #6	The 3D printer must be able to be procured for minimal cost.

Table 2. Eight Design Characteristics of a Humanitarian 3D Printer. Source: Savonen et al. (2018).

Design Characteristic Number	Design Characteristic Description
Design Characteristic #1	Fused Filament Fabrication (FFF)
Design Characteristic #2	Open-Source RepRap Design
Design Characteristic #3	Modular Design
Design Characteristic #4	Separable Frame
Design Characteristic #5	Protected Electronics
Design Characteristic #6	On-Board Computer System
Design Characteristic #7	Flexible Power Supply
Design Characteristic #8	Climate Control Mechanisms

Following the layout of the 3D printer requirements and design characteristics, Savonen's team discussed the Kijenzi 3D printer and how that particular printer either meets or does not meet the requirements and design characteristics for a HADR 3D printer. As seen in Figure 1 and Figure 2, the Kijenzi 3D printer's low profile and easy assembly and disassembly could provide several benefits for the conduct of HADR operations.

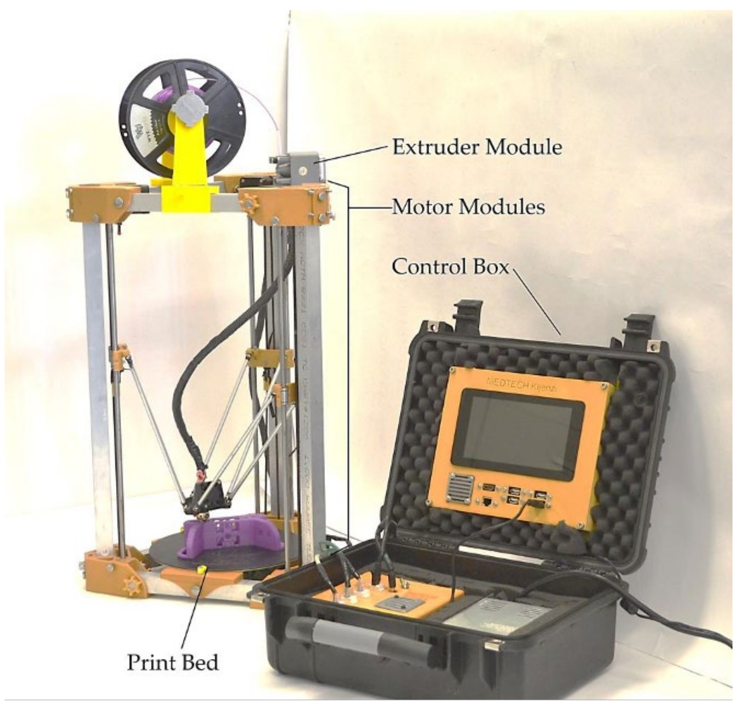

Figure 1. Kijenzi 3D Printer Assembled Control Box and Printer Bed. Source: Savonen et al. (2018).

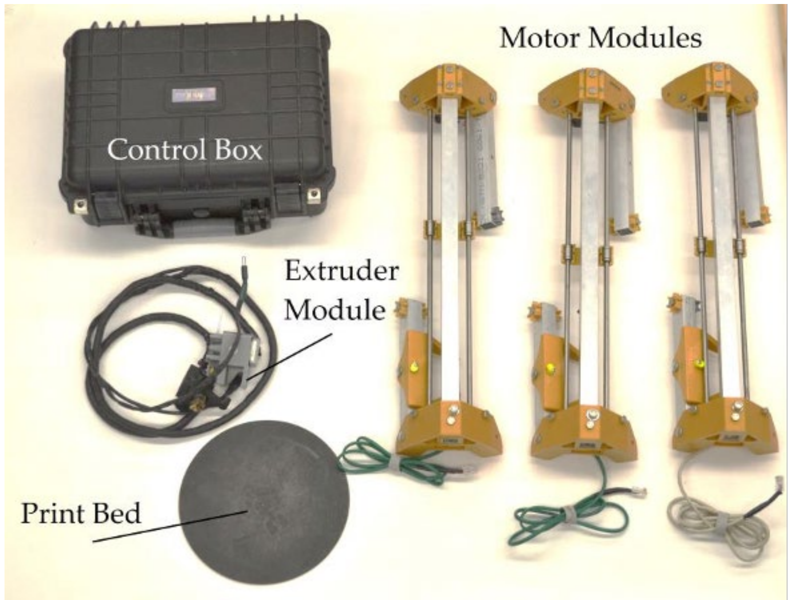

Figure 2. Kijenzi 3D Printer Disassembled Control Box and Printer Bed. Source: Savonen et al. (2018).

The Kijenzi 3D printer offers several other benefits for HADR operations (Savonen et al., 2018). First, the printer can integrate with various energy sources such as batteries, generators, and solar power motors. The printer can integrate into the host nation power infrastructure if available, but the printer's highly flexible power sources do not make this host nation support a requirement. Furthermore, with the advances in solar energy capabilities, this 3D printer has the capability to operate autonomously in austere environments without the need for the fuel source to be shipped from outside and throughout the host nation. Second, as seen in Figure 3, the printer's small profile and light weight allow for easy transport on multiple platforms to remote locations. Third, by only requiring raw materials, packaging and several other shipping constraints are reduced to allow for far more efficiencies in shipping only raw materials—not specific items—throughout the global supply chain. Fourth, and finally, as seen in Figure 4, the range of high-demand, low-density medical items provide robust and rapid capabilities to medical teams on the ground. The parts depicted include a pill sorter, a slide dryer, a uterine model, a replica of umbilical cord clamps, and a replacement knob for a microscope. Even though these parts provided more support to USN medical and civilian medical organizations instead of Marine Corps operations, the key difference was not the equipment or the hardware but a change in the software or the computer aided design (CAD) file. Thus, even though the examples are medical in nature, repair parts and other unique items can be created for the Marine Corps by a printer similar to the Kijenzi 3D printer.

Figure 3. Packed Kijenzi 3D Printer. Source: Savonen et al. (2018).

Figure 4. 3D Printed Medical Parts. Source: Savonen et al. (2018).

In 2020, another research team with the Netherlands Royal Army also looked at the benefits of AM to HADR operations. Even though they did not review a particular printer, this team further expanded upon on the unique challenges of conducting HADR operations with similar conclusions to Savonen and his team's research. These challenges include parts requirements that are not known until the disaster has already occurred, local infrastructure that will most likely be damaged and thus hinder transportation and distribution, a lack of organic transportation equipment to augment foreign aid organizations, local governmental that will likely not be in full control, nefarious nonstate actors that present a threat of physical violence, and the mass quantities of various items that are required (Boer et al., 2020). Boer and his team recommended several propositions on the benefits of AM. However, as depicted in Table 3, two in particular demonstrate how AM could benefit organizations in the execution of HADR operations. Boer and his team further discussed the advantages of centralized or distributed AM spare parts supply chain management. A centralized process benefits items with a below-average demand and long manufacturing lead times, while a distributed process benefits items with unpredictable demand and short manufacturing lead times (Boer et al., 2020). Consequently, supply chains should employ both centralized and distributed AM activities and tailor the AM capabilities to produce particular items that are best suited for the location of the 3D printer. Savonen, Boer, and their teams highlight that the international community is focused on incorporating AM in the conduct of HADR operations. These researchers and international organizations offer a unique partnership for the Marine Corps to pursue in developing and advancing its own 3DP capabilities.

Table 3. Two Propositions to the Benefits of AM. Source: Boer et al. (2020).

Proposition Number	Proposition Description
Proposition #1	AM can improve spare parts availability in terms of speed, location and life cycle and hence make military and humanitarian missions more responsive.
Proposition #2	AM improves sustainability, in terms of environmental impact, of military and humanitarian operations at large, but in particular spare parts supply during missions.

Outside of HADR operations, the international community is advancing other AM initiatives in not only the development of spare parts but also the creation of buildings and other larger objects. As depicted in Figure 5, a Danish company in 2017 constructed a building on demand (BOD) with the dimensions of 8 × 8 × 6 meters with a print speed of 2.5 meters per minute. This accomplishment not only resulted in the construction of a building within days—not weeks or months—but also within the strict European norms and standards (Hanna, 2019). As depicted in Figure 6, a French company in 2017 developed its own 95 square meter home called a YHNOVA home. Even though the project took several months to complete, construction of the dwelling itself only took a few days. Finally, the company utilized advance construction technologies and combined several previously separate processes into one. This combination drove down construction time, which in turn drove down energy requirements to construct the building (Hanna, 2019). Finally, as depicted in Figure 7, an Italian company in 2018 designed and built a 100 square meter modular home with AM technology. This modular home was separated into 35 different parts with printed times of 60 to 90 minutes per part. This speed allowed for the entire home to be built within 48 hours. Furthermore, being modular, the building is capable of easy expansion as well as relocation (Hanna, 2019). These examples show that the international community is making significant strides in AM with regard to increasing speed of large-scale construction, having highly specialized structures, reducing energy costs for large-scale production, and incorporating modularity into their printing—thus allowing for mobility and flexibility in their construction efforts. All these technological advances can have significant impacts on Marine Corps implementation of AM throughout Marine Corps doctrine.

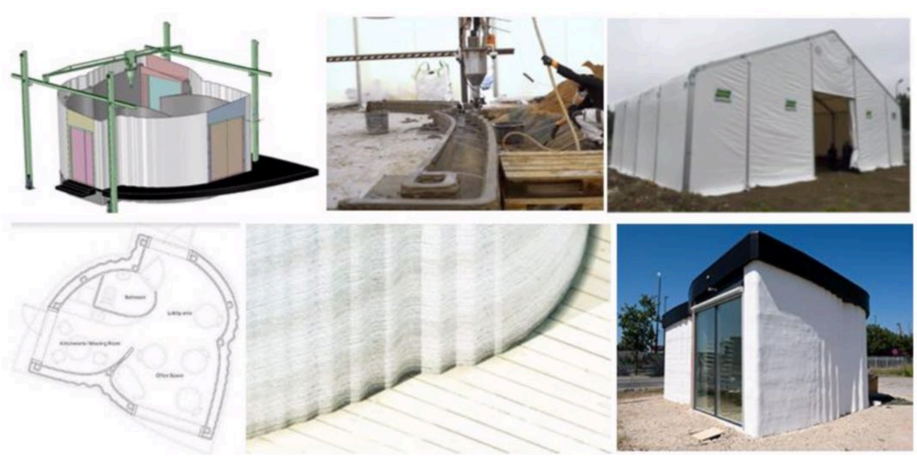

Figure 5. BOD Construction in Denmark. Source: Hanna (2019).

Figure 6. YHNOVA Construction in France. Source: Hanna (2019).

Figure 7. 3D Construction in Italy. Source: Hanna (2019).

In addition to new materials such as concrete in the application of AM, the civilian sector is pursuing the application of AM into the creation of circuitry. In May 2020, HENSOLDT, an aerospace company, developed and printed "the first 10-layered printed circuit board (PCB) mounting electronic components on both sides of the board" (Elinoff, 2020). The creation of PCBs with AM demonstrates the technology's ability to solder at a highly precise measurement while also printing on both sides of the PCB. As the technology advances, more sophisticated circuitry can be created to allow AM to produce not only simple polymer designs but also highly technical circuit boards in a wide range of electronic equipment.

However, any technological breakthrough will present an element of risk or potential vulnerability that adversaries will seek to exploit in an effort to either eliminate or diminish the benefit the technological advancement provides. The breakthroughs in AM are no different, and adversaries to the United States will seek out vulnerabilities to exploit. In 2016, one team of researchers (Zeltmann et al., 2016) presented two potential attack vectors to interfere or damage the credibility of AM technology. The first vulnerability discussed was embedding a defect to test tensile strength when under load and not under load. The test also aimed to determine if the defect could remain undetected from ultrasonic inspection. This study found that the defect could remain undetected but presented little effect to tensile strength of the item when not under a load. However, tensile strength was affected when the item was placed under tension or load. The second vulnerability tested was altering the printer direction but leaving the CAD file and materials themselves untampered. Figure 8 depicts the various printing directions. The researchers determined that the alteration of the direction of the printer had significant effects to tensile strength and increased failure rates during strain testing but remained undetected as the printer direction was the only variable change (Zeltmann et al., 2016).

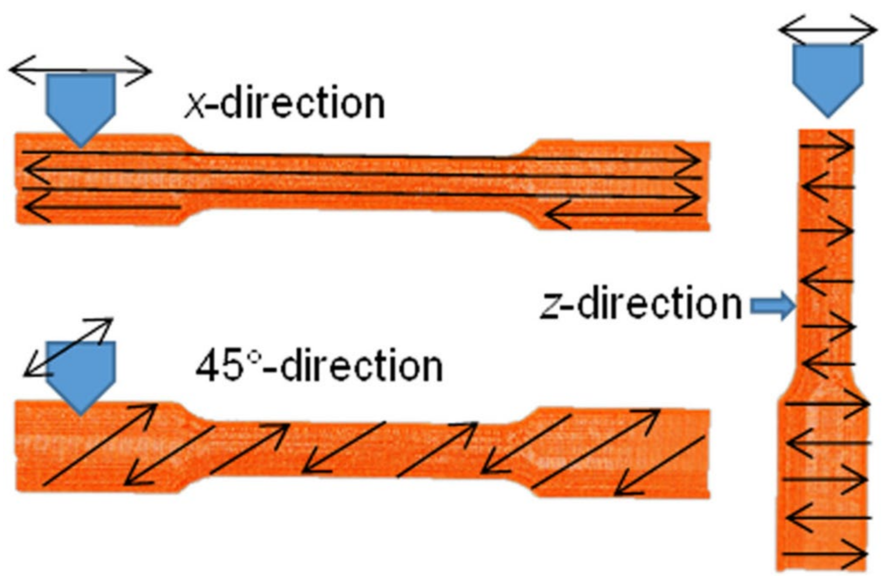

Figure 8. Printer Direction Vulnerability Test. Source: Zeltmann et al. (2016).

The Fourth Industrial Revolution will have significant impacts on the U.S. military. The field of AM is no exception, and the global civilian sector is seeing rapid growth in AM technologies. The miniaturization of this technology, such as the Kijenzi 3D printer, is only one of several examples that will impact the abilities to conduct a wide range of military and civilian operations and not just HADR operations. The large-scale construction efforts being undertaken in Europe are also only a few examples of the size and scale that AM can achieve. Finally, with the advances of PCB and circuitry printing, the range of materials available for print are expanding in scale as well. However, any technological advancement presents an element of risk. The Marine Corps can learn from the lessons of both miniaturization as well as increased scale of AM technology but also must remain vigilant in identifying the risks presented with this new technology.

B. DOD AND OTHER MILITARY DEPARTMENTS' USE OF AM

In 2018, Secretary of Defense James N. Mattis published the U.S. National Defense Strategy (NDS). This document, nested underneath the National Security Strategy, discussed an emergence from a "strategic atrophy" (DOD, 2018, p. 1) to a new era where near peer adversaries were the threat to the U.S. national defense, and the United States could not rely on an overwhelming advantage against hostile state and nonstate actors. The United States will face threats across all five domains of warfare (air, land, sea, space, and cyber). In response to this paradigm shift, Secretary Mattis (2018) directed the joint force to be more "lethal, resilient, and rapidly adapting" (p. 1). He stated specific lines of effort (LOE) for the DOD to focus their resources, including development of advanced autonomous systems and a more resilient and agile logistics network.

Even though Secretary Mattis did not specifically mention AM technology, in a 2016 article, Amanda Schrand highlighted how AM could support the development of advanced autonomous systems and a more resilient and agile logistics network. She stated that

> if such technologies become widespread, the acquisitions process could be reduced to its simplest form and become much more agile and rapid via AM. For example, printers could be acquired and fielded along with the

materials and files responsible for on-demand, in-the-field printing vehicles and systems. (Schrand, 2016, p. 85)

She elaborates that AM can provide relatively simple autonomous vehicles that are modular in design, which allows greater operational capabilities at a decreased cost. However, she warns that due to the bureaucratic nature of the DOD, synchronized integration across the DOD will be a challenge that must be addressed early and extensively. Failure to address those concerns will result in decreased AM benefits, duality of efforts, and increased costs (Schrand, 2016).

Prior to the publication of the NDS, the DOD published an AM roadmap in 2016 to guide and focus its and the military services' efforts to integrate AM throughout the entire department. As seen in Figure 9, the four major subgroups underneath the DOD are the Defense Logistics Agency (DLA), Department of the Army, Department of the Air Force, and DON.

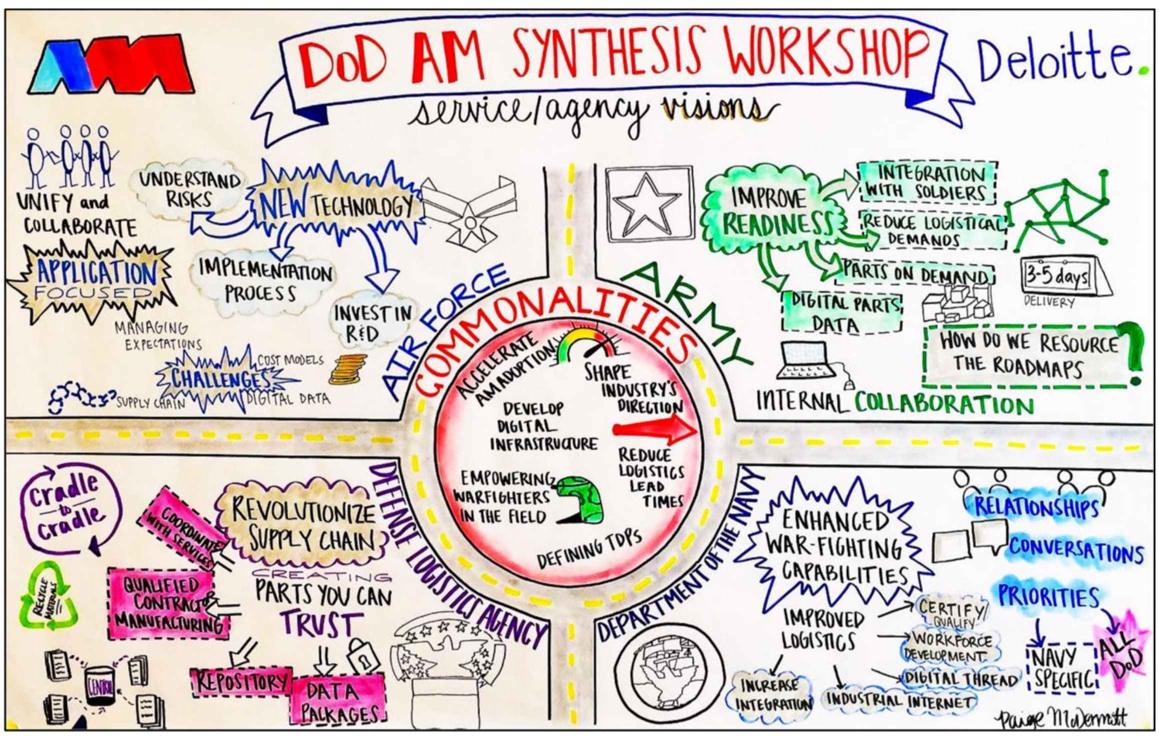

Figure 9. DOD AM Roadmap. Source: Department of Defense (DOD, 2016).

This document also provided three LOEs for the department and military services. The three are maintenance and sustainment, deployed and expeditionary, and new part/system acquisition. As depicted in Table 4, the three LOEs have sub-LOEs which cross between two or more of the overarching LOEs.

Table 4. DOD AM LOEs. Source: DOD (2016).

Line of Effort #1: **Maintenance and Sustainment**
LOE #1.1: **Manufacture of parts** typically produced using conventional manufacturing
LOE #1.2: **AM repair** of conventionally manufactured parts
LOE #1.3: **Manufacturing aides** for support to conventional manufacturing
LOE #1.4: **Prototyping** for rapid innovation and reverse engineering
Line of Effort #2: **Deployed and Expeditionary**
LOE #2.1: **Manufacture of parts** typically produced using conventional manufacturing
LOE #2.2: **AM repair** of conventionally manufactured parts
LOE #2.3: **Prototyping** for rapid innovation and reverse engineering
Line of Effort #3: **New Part/System Acquisition**
LOE #3.1: **New parts/systems** designed for AM and manufactured using AM
LOE #3.2: **Manufacturing aides** for support to conventional manufacturing
LOE #3.3: **Prototyping** for rapid part/system development

LOE #1, Maintenance and Sustainment, addresses how AM can augment traditional manufacturing techniques in the manufacturing of repair parts. In 2016, the focus was not on cost savings but on how AM could diminish the time requirement to replace the broken item. Similar to LOE #1, LOE #2, Deployed and Expeditionary, focuses on the repair and replacement of broken items but in austere and remote locations. Location considerations further refine this LOE to focus on environmental factors such as weather and the potential usage of host nation feedstock materials. Finally, LOE #3, New Part/System Acquisition, focuses efforts on integration of AM to assist with manufacturing aides and prototyping of new systems (DOD, 2016). These three LOEs are the foundation for follow-on policies and directives for the DOD and its military services.

One source document for the NDS written in 2018 was the U.S. Senate's National Defense Authorization Act (NDAA) for Fiscal Year (FY) 2017, which recommended "the

DOD to more aggressively pursue AM capabilities to improve readiness" (Department of Defense Inspector General [DODIG], 2019, p. 2). As such, the under secretary of defense for acquisition, technology, and logistics (USD[AT&L]) published a congressional report on the current progress in integrating AM throughout the DOD (Under Secretary of Defense for Acquisition, Technology, and Logistics [USD(AT&L)], 2017). USD(AT&L) selected the Manufacturing and Industrial Base Policy (MIBP) as the DOD lead agent for AM matters (DODIG, 2019). Also, the USD(AT&L) (2017) acknowledged that the initial efforts had been primarily "grass roots" (p. 1), but efforts had been made to a more "higher-level coordinated activity" (p. 1) for AM integration. One such activity being pursued at the DOD level was the certification and qualification of AM parts across the DOD. The report also reiterated the importance of the three LOEs laid out in Table 4. However, the major focus of the report was a discussion on the duality of efforts across some or all four military services and agencies without crossover coordination and synchronization. The report's findings showed that out of the 29 objectives across all military services, 20 of those objectives are being pursued separately by all four military services and agencies. As such, the report recommended the formation of the Joint Additive Manufacturing Steering Group (JAMSG) and Joint Additive Manufacturing Working Group (JAMWG) to synchronize AM activities across the four military services and agencies. One significant synchronization activity that was recommended was the pursuit of an online portal to store, disseminate, and standardize CAD files for DOD-wide usage (USD[AT&L], 2017).

As stated, each military service provided an internal report to their current activities within AM. The DON identified five focus areas for the integration of the three LOEs laid out by USD(AT&L). Table 5 depicts those focus areas.

Table 5. Five Focus Areas to DON AM Integration. Source: USD(AT&L) (2017).

Five Enterprise-Wide Challenges to AM Integration
1. Expeditionary and Operational Manufacturing
2. Qualification and Certification
3. Digital Thread
4. Workforce Development
5. Business Processes

For the first focus area, the DON highlighted several examples of how they are using AM to overcome the challenges of logistical support in expeditionary and austere environments. One example included the 3DP of an unmanned aircraft system (UAS), which only cost $3,000 to produce compared to traditional UASs that cost between $200,000 to $250,000. This system simplicity also allowed the same Marine or Sailor to print and operate the UAS. Another example highlighted was the 3DP of a helicopter helmet visor clip that had a 9-month lead time and cost $300. By manufacturing the item with 3DP, the DON reduced the cost per unit to $0.75 and printed 100 clips in 10 days. For the second focus area, the DON is concentrating on primarily aircraft components that require a high level of qualification and certification and is working to standardize the technical data packages (TDP) to be synchronized across the DOD. For the third focus area, the Marine Corps has developed an online portal called Marine Maker to store and disseminate all CAD files across the Marine Corps. NAVAIR is developing a similar portal to store and disseminate CAD files through the USN. For the fourth focus area, the USMC has developed mobile training teams and created Marine Maker spaces as stated in MARADMIN 594/17. For the fifth and final focus area, the DON stated that they will publish a comprehensive AM contracting guide (USD[AT&L], 2017).

Following the 2017 report, the now under secretary of defense for acquisition and sustainment (USD[A&S]), formerly the USD(AT&L), published for the first time an interim policy on AM to synchronize efforts across the DOD. This policy was published in March 2019 with a revision published in June 2020. The policy primarily discussed the roles and responsibilities of the USD(A&S) and the four military services and agencies.

One key responsibility tasked to DLA was the creation of the aforementioned online repository for all CAD files. However, the policy did not elaborate on the cybersecurity considerations or which agency inside the DOD would consider cybersecurity factors for AM integration. This seven-page policy only provided high-level tasks and lacked important specifics on AM activities within the DOD.

Following the 2016 roadmap, the 2017 report, and the 2019 policy publication, the DODIG published in 2019 a report analyzing the DOD's efforts in integrating AM. The report started by acknowledging that the DOD had been utilizing AM for the past 15 years and began collaborating with America Makes in 2012 to coordinate efforts within the DOD and to capture AM advances in other governmental agencies, private industry, and universities. The DODIG praised several aspects of DOD's implementation of AM in the department. First, it acknowledged that the DOD had expanded its AM capabilities beyond maintenance activities into the 3 LOEs discussed in Table 4 (DODIG, 2019). Second, DODIG approved of the creation of the JAMSG and JAMWG to address data sharing, cybersecurity concerns, and AM part qualification and certification. Third, DODIG acknowledged the creation of Joint Additive Manufacturing Model Exchange (JAMMEX), a DLA-operated online joint portal for CAD files. Fourth, DODIG approved of the DOD's maintenance focus efforts on low-quantity and high-demand items to realize the most cost and maintenance time savings. It provided several examples, including the F-35 landing gear door bump stop, which—if broken—traditionally requires the purchase of the entire landing gear assembly for $70,000; however, the USN used AM to produce the bump stop for only $0.75 and immediately installed the part once printed. Fifth and final, the report commended the DOD's use of AM in mitigating issues with parts not being available from original manufacturers or from traditional sources and in improving existing parts (DODIG, 2019).

However, the DODIG report noted several areas of concern. First, the significant delay in publishing a DOD-wide policy until 2019 allowed for the four military services and agencies to independently develop their own processes, procedures, and systems for integrating AM into their organizations. The DODIG noted,

> For example, both the Air Force and the Navy are using AM to produce parts and tools to sustain the C-130 Hercules aircraft (C-130). By not sharing information regarding the design, type of material used, and other technical data, both Military Services could be working on the development of the same part or developing a part that has previously been engineered by the other Military Service. (DODIG, 2019, p. 16)

This created the duality of efforts that the 2017 report to Congress highlighted and that Schrand (2016) foresaw in her article. Second, even though the DODIG commended the DLA for creating JAMMEX, it criticized the DLA for not providing the military services with the policies and procedures for integrating their own repositories into the JAMMEX repository as well as what materials were used, a common stock numbers list, and file formats to be used. For example, "The Air Force is using an Access database and Excel spreadsheets to track AM parts produced or waiting for approval" (DODIG, 2019, p. 15). Third and finally, the DODIG report highlighted a lack of tracking AM systems throughout the DOD into one repository. The DODIG stated that this lack would result in duality of assets being co-located geographically or services using internal AM assets to their service while other military services might have AM systems geographically closer to the point of need (DODIG, 2019). As of June 2020, the interim policy still does not dictate to track AM systems throughout the DOD in one repository.

In addition to these criticisms, the DODIG provided a list of four overarching recommendations. First, military services and agencies should use standard formats for reporting AM data. This reporting should include data on parts produced using AM and AM equipment by military services as well as the amount spent on AM by both military services and the DLA. Second, the under secretary of defense for research and engineering (USD[R&E]) should develop policy to standardize the cataloguing of AM parts. Furthermore, USD(R&E) should require all military services and agencies to use a single repository for AM CAD files. One such system that would fulfill this requirement would be JAMMEX. Third, USD(R&E) should require military services and DLA to require all subordinate guidance and policies on AM to include language regarding contracting, acquisitions, logistics, and senior management officials to receive AM training. Fourth, the military services, including the Marine Corps, should task their respective AM leads to develop a process for tracking and updating a complete list of AM parts and parts waiting for approval, as well as the ability to share this list with other services. DODIG did state that JAMMEX could fulfill this recommendation as long as the military services' own repositories could replicate with the JAMMEX repository. Finally, the DODIG recommends that all military services and agencies identify the appropriate funding levels for AM pursuits and appropriate population size for of personnel pursuing AM initiatives (DODIG, 2019).

In parallel to the DOD's implementation of AM, the DON and the USN have also been implementing policies and guidance on DON-wide implementation of AM. One such DON policy, published in 2017, was the DON's Additive AM Implementation Plan V2.0. This document would have two overarching goals of increasing readiness and sustainment as well as enhancing warfighter capabilities. In an effort to achieve these goals, the document lists five objectives. First, the DON will develop and implement a process to rapidly qualify and certify AM parts. Second, the DON will create a secure repository of AM parts to provide process integration across the DON for AM data, infrastructure, and tools. As of 2019, "The Navy uses the JTDI [Joint Technical Data Integration], Excel spreadsheets, and an Access database to track AM parts" (DODIG, 2019, p. 15). Third, the DON will create a training and certification program that will be available to all DON personnel. Fourth, all subsequent guidance and policies will consider and address business practices, contracting, intellectual property, and legal and liability considerations, when applicable. Fifth, the DON will seek to employ AM in operational environments and drive manufacturing to as close to the point of need as possible (Secretary of the Navy, 2017).

Similar to the DOD, the DON has seen the benefits of AM when addressing the obsolescence of parts (Schrand, 2016) and the ability to decrease maintenance costs and time. The DODIG noted,

> The Navy used AM to produce an MH-60R Sea Hawk Helicopter (MH-60R) sonar system cover, which was not always available in the supply system. The AM-produced sonar system cover eliminated corrosion of the traditionally manufactured cover, reduced the lead time from 2 years to 1 week, and decreased cost from $ [redacted] to $ [redacted] per cover. (DODIG, 2019, p. 9)

One unique benefit of AM that primarily supports DON operations is the expanded ability to operate within the Chinese weapon engagement zone (WEZ; Office of the Deputy Assistant Secretary of the Army for Research and Technology, 2019). As seen in figures 10 and 11, the Chinese WEZ presents both global and regional obstacles to DON SLOCs. "This aggressive pursuit of AM will ultimately enable a future 'Self-Sustaining Naval Force' that is free of vulnerable lines of communication and dedicated logistics assets" (Secretary of the Navy, 2017, p. 5).

Figure 10. Chinese WEZ Global Impact. Source: Missile Defense Project (2020).

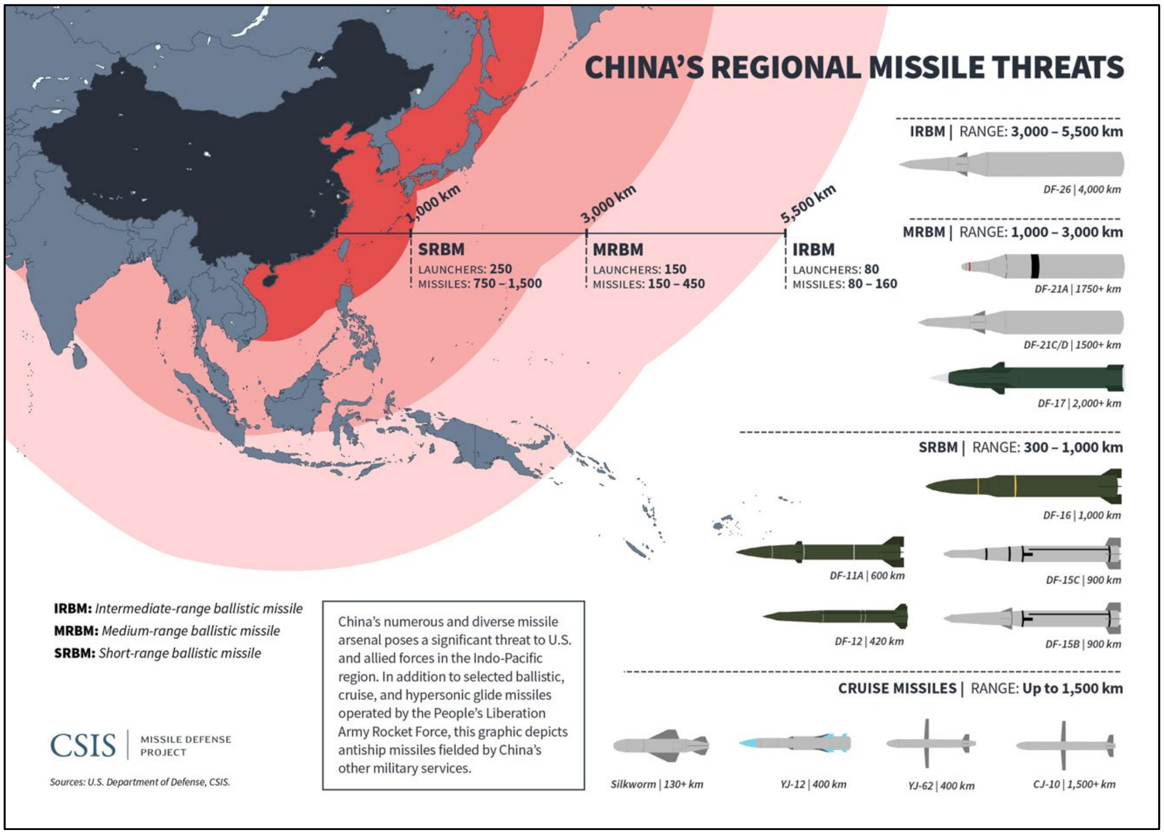

Figure 11. Chinese WEZ Regional Impact. Source: Missile Defense Project (2020).

From Table 6, Class I, III, and V sources of supply require significant quantities of raw materials. Thus, the benefits of AM to these classes of supply in expeditionary or austere environments would be limited. AM could provide significant benefits to other classes of supply, but most specifically, Class VIII and IX.

Table 6. Classes of Supply. Source: Joint Chiefs of Staff (2019).

Class Number	Class Description
Class I	Subsistence
Class II	General Support Items
Class III	Petroleum, Oils, Lubricants (POL)
Class IV	Construction/Barrier
Class V	Ammunition
Class VI	Personal Demand Items
Class VII	Major End-Items
Class VIII	Medical Material/Medical Repair
Class IX	Repair Parts (Less Medical Special Repair Parts)
Class X	Code as Zero (0): Materials Not Included in Class I–IX

Even though AM provides unique benefits to the DON, AM also has its own DON-specific challenges. Once such challenge is printing aboard ships while underway. Even though 3DP has occurred aboard ships such as the USS *Essex* (CV 9) "to demonstrate the ability to additively develop and produce shipboard items such as oil reservoir caps, drain covers, training aids, and tools to achieve performance improvements" (Government Accountability Office [GAO], 2015, p. 20), environmental factors have significant impacts to printing aboard ship. Such factors include humidity, vibrations, and motion that could affect the quality of the printed item (GAO, 2015).

The DOD and DON literature highlights that the Marine Corps–owned AM initiatives must be nested under both DOD and DON policy for the Marine Corps to truly maximize the benefits of AM. Without considering these policies and guidance, issues will arise such as duality of efforts and increased costs (Schrand, 2016). These issues will ultimately affect the Marine Corps' ability to fulfill Secretary Mattis's (2018) directive of being a "lethal, resilient, and rapidly adapting" (p. 1) force in readiness.

C. MARINE CORPS' AM INITIATIVES

As the previous chapter of this research captured, the primary source documents for AM integration in the Marine Corps are the four MARADMINs and MCO 4700.4. The first MARADMIN was published in September 2016, and the MCO was published in March 2020. During this period of time and slightly before, the Marine Corps had published other literature and research, conducted various projects and exercises, and created and expanded the AMOC's AM efforts throughout the Marine Corps. All of these actions sought to expand AM's reach to fulfill the DON's overarching goals of increasing readiness and sustainment as well as enhancing warfighter capabilities (Secretary of the Navy, 2017) and adapting the Marines Corps logistics systems to be more responsive and lethal—in line with Secretary Mattis's (2018) NDS guidance.

The first primary piece of literature for the Marine Corps' integration of AM came from R. W. Appleton & Company Inc., which provided an overview of AM initiatives in 2014. Even though it is a dated review of the Marine Corps' progress, the report highlighted some points and issues that still are relevant. First, Appleton (2014) stated,

> Unlike traditional manufacturing methods that require expensive and time consuming tooling setup, A/M goes straight from CAD drawing to the printer with only a software interface. The per-item cost of one is no more than for one thousand. Economy of scale is less important. The converse of this is that for large production runs of identical items, traditional methods usually remain the best choice. (p. 10)

Second, as of 2014, the preponderance of 3D printing companies are not headquartered in the United States, which presents significant security concerns when employing commercial printers for military and national defense use. Third, Appleton stated,

> Because of the elimination of design constraints, it is possible to manufacture much stronger items weighing less than their traditionally made counterparts. And because of the near elimination of waste, it is possible to make them at reasonable cost. (Appleton, 2014, p. 10)

Fourth, as AM requires the TDP in the form of a CAD file, acquisitions of new weapon systems will require the additional purchase of the TDP with the system, which many suppliers will be resistant to providing. However, that additional purchase "would more than offset the price tag" (Appleton, 2014, p. 24). Fifth and finally, the purchasing of these CAD files will allow the storage of files in lieu of physical end-items or parts. This change in storage will either greatly diminish or remove entirely the employment of a proverbial iron mountain stockpile (Appleton, 2014). Even though dated, these five lessons still bear relevancy to AM initiatives today.

Other literature includes DC I&L's 2017 roadmap, where then DC I&L, Lieutenant General Michael G. Dana, stated that the primary classes of supply transported through the Marine Corps supply system are Class I, III, and V (Deputy Commandant for Installations and Logistics [DC I&L], 2017). As previously discussed regarding classes of supply, even though AM would not benefit those three classes, DC I&L and the Marine Corps still see the advantages that AM technology could offer. As such, LtGen Dana went on to state,

> Emerging technologies provide great promise, and will give us [the Marine Corps] the ability to offset enemy capabilities by resupplying faster, producing on-demand parts and outmaneuvering our enemies on the battlefield. Our NexLog capability development efforts are focused on three key thrust areas: additive manufacturing, smart logistics and unmanned capabilities. (DC I&L, 2017, p. 7)

He elaborated to say that AM would allow for the flattening of the supply chain to place logistics requirements at the point of need (DC I&L, 2017) for those classes of supply outside of I, III, and V.

In addition to these reports and literature on the benefits of AM, the Marines Corps has conducted exercises and projects to further expand AM's capabilities for the Marine Corps. Several examples of increasing readiness and sustainment already exist, including the printing of H-1 helmet visor clips, rifle optic flash covers, and other small plastic repair parts and the usage of hybrid manufacturing, which is a combination of AM and traditional or subtractive manufacturing with metal material. Furthermore, other examples of enhancing warfighter capabilities are the acquisitions of lightweight polymer .50 caliber ammunition and Exercise Burgeon Strike, which sought to assess the training and execution of printing large scale concrete items and structures.

Similar to the F-35 landing gear door bump stop and the MH-60R Sea Hawk sonar system cover, the Marine Corps has also seen AM benefits to both cost and time for repairing low-quantity, high-demand items. As previously mentioned, one example includes the use of AM to print helicopter helmet visor clips—reducing maintenance downtime from 270 days to 10 days and decreasing cost from $300 to $0.75 per helmet visor clip (DODIG, 2019). Another example includes the printing of rifle optic flash covers. Traditionally these items cost $54 each, but when printed using AM, they only cost

$0.57 (Douglas, 2020). A third example includes the use of a LulzBot TAZ 6 3D printer aboard the USS *John P. Murtha* (LPD 26) and USS *Boxer* (LHD 4) (Fuentes, 2019). While aboard ships, Combat Logistics Battalion 11 Marines printed spotting scope caps, subscriber identify module (SIM) card trays for satellite phones, and several other items. Even though these items were relatively cheap to manufacture, the decrease in maintenance downtime allowed these items to quickly protect other high valued systems, which—in turn—still saved significant dollars by printing these items on demand in a timeframe of hours or days instead of waiting for them to be transported to the ship, which would have taken weeks or months (Fuentes, 2019). Finally, the Marine Corps is pursuing how hybrid manufacturing can benefit readiness and sustainment (Zelinski, 2019). Benefits of AM production are the decrease in waste or scrap and the ability to produce the part outside of the production facility, but a benefit of subtractive or traditional manufacturing is the precision that milling and drilling provide, which AM cannot do solely. By combining both of these technologies into one system, the benefits of each are realized while diminishing or removing entirely the drawbacks of the standalone technology (Zelinski, 2019). Furthermore, hybrid manufacturing does not just increase readiness and sustainment but also increases warfighter capabilities by allowing for alteration of items for increased benefits and production capabilities of those items in an operational environment if the appropriate materials are on hand.

Another example of AM increasing warfighter capabilities is the acquisition of lightweight polymer .50 caliber ammunition (Athey, 2020). This $10 million acquisition project seeks to replace the metal casings and metal ammunition containers with a lighter weight polymer casing and container, respectively. The contractor will also replace the metal links with a lighter-weight nylon link. The reduction in weight for each ammunition container will be approximately 20 pounds. This reduction will not only allow Marines to carry less weight or more ammunition at the same weight requirement, it will also reduce lift requirements such as the number of vehicles or helicopters transporting large quantities of the ammunition. Thus, AM does provide benefits in the transportation of Class I, III, and V by producing Class V at the point of need but then making the transportation of Class V less demanding on the supply chain with the reduction of weight. Additionally, as the polymers and nylon absorb less heat than metal, the weapons system itself will remain cooler while firing prolonged bursts, thus diminishing the risks of overheating or jamming the weapons system (Athey, 2020).

Another example of increasing warfighters' capabilities is seen during Exercise Burgeon Strike. This exercise was a 3-day joint exercise between the USMC, the United States Air Force (USAF), and the United States Army Corps of Engineers. Its objective was to test whether untrained Marines and Airmen could be trained to construct concrete buildings in only a few days (Jagoda et al., 2020). The exercise was subdivided into two parts. The first part was a training program for the personnel on the AM equipment that would be used in the second part. The second part was the actual construction by the newly trained personnel. "While four of the eight Marine and Air Force personnel in attendance had prior experience with the 3D-printed construction process, none of the personnel had ever written G-code" (Jagoda et al., 2020, p. 3). G-code is the software language used to print the concrete buildings. All personnel were successfully trained in only 1 day on both the equipment and the G-code software. The next 2 days consisted of the actual printing of the dragon's teeth (as depicted in Figure 12) and an entry control point, barracks hut, and defensive fighting position (as depicted in Figure 13).

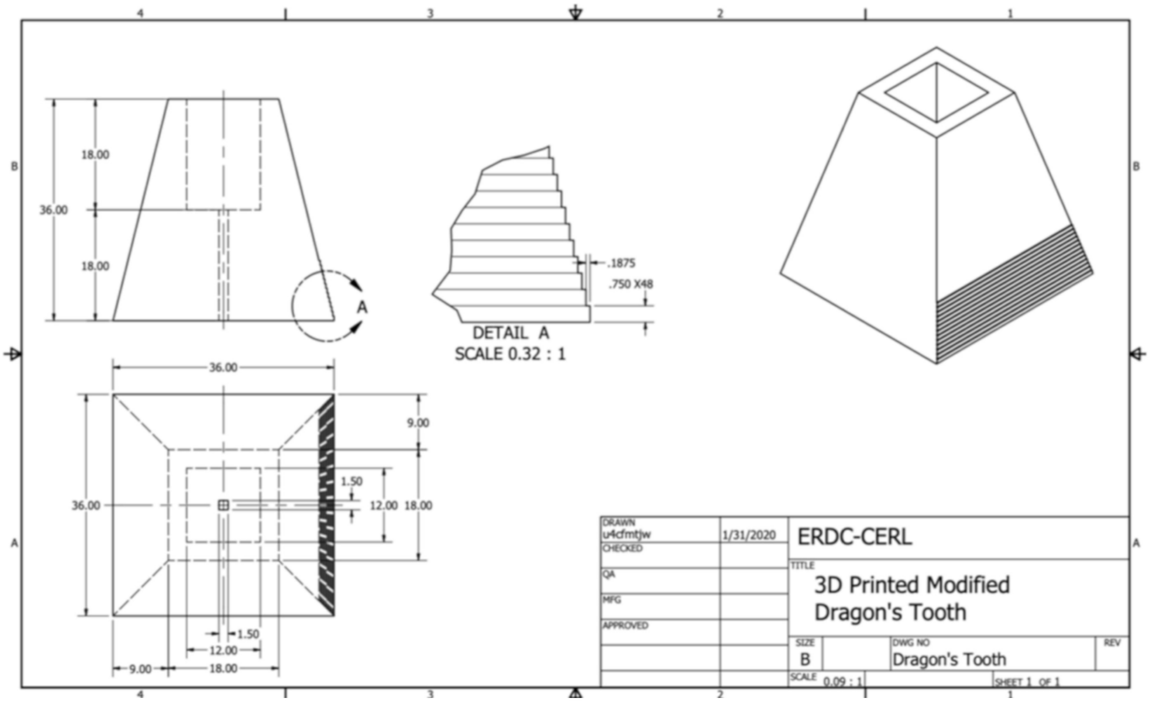

Figure 12. Dragon Teeth Dimensions. Source: Jagoda et al. (2020).

Figure 13. Entry Control Point, Barracks Hut, and Defensive Fighting Position. Source: Jagoda et al. (2020).

The printer used was an Automated Construction of Expeditionary Structures (ACES) Lite 2, which is a prototype, deployable 3D printer that is capable of being deployed in 30 minutes by a trained team of four personnel but only requiring a minimum of two personnel for operations (Jagoda et al., 2020). To ensure higher quality printing, a bagged concrete material mix was used to ensure consistency of materials throughout the entire printing process. Jagoda et al. (2020) noted,

> The downside of using a bagged material mix for 3D printing is that it could be difficult, expensive, or time-consuming to procure in a remote, isolated, or expeditionary environment, depending on the location. The benefits of more consistent material performance must be weighed against the cost and logistics trade-offs. (p. 5)

The dragon's teeth were each printed in under 1 hour and were able to be transported after 2 days to allow the material to dry. If made conventionally, the dragon's teeth would have taken from approximately 3 to 6 hours. Unfortunately, because a bagged material mix was used, the cost for an AM dragon's tooth was $750—which is more expensive than a conventionally manufactured dragon's tooth, which would cost $500. The majority of the cost increase came from the usage of the bagged material. Thus, one way to offset the cost increase would be to use the bagged material mix for the frame while using a cheaper material as filler (Jagoda et al., 2020). Regardless, the cost savings seen in maintenance repair parts will likely not be achieved to the same scale with 3DP concrete buildings.

Even though this AM exercise did not achieve cost savings, several other benefits were documented by manufacturing these concrete items with AM technology. First, an "advantage of 3D-printed construction over conventional construction is the elimination of the need for formwork, which in turn reduces material consumption, construction time, labor demand, environmental impact of materials, and cost" (Jagoda et al., 2020, p. 6). The costs savings mentioned in this quote refer to the cost savings with the decrease in labor as well as the decrease in environmental costs when compared to traditional manufacturing techniques. Second, AM construction allows for continuous printing, with limited time needed for cleaning and maintenance. Third, AM is more autonomous when compared to conventional construction. This automation in turn results in reduced labor demand and diminished human error per item (Jagoda et al., 2020).

The last major Marine Corps AM effort between 2016 and 2020 was the transfer of the lead AM agent from NexLog–AM to the AMOC. The AMOC was established in January 2019 and reports directly to MCSC (Audette, 2019). In concert with Installation and Logistics (I&L) personnel, the AMOC has create six overarching goals of AM in the Marine Corps as depicted in Table 7 (Douglas, 2020). One key goal, Goal #3, seeks to drive innovation from the bottom up, while still providing centralized control of implementation as seen with the publication of MCO 4700.4 (Douglas, 2020).

Table 7. Marine Corps AM Overarching Goals. Source: Douglas (2020).

Goal Number	Goal Description
Goal #1	**Speed and Flexibility**: In-field fabrication close to the forward edge of battle.
Goal #2	**Adaptability**: Rapid prototyping for emergent needs
Goal #3	**Warfighter Innovation**: Designs led bottom-up
Goal #4	**Risk Reduction**: Overcome obsolescent and long lead time parts
Goal #5	**Customizable**: Bespoke solutions for missions or people
Goal #6	**Ability**: Unique designs for performance and efficiency

Two significant LOEs in achieving these six goals are the creation of programs of record (PORs) for the tactical fabrication (TACFAB) and expeditionary fabrication (XFAB) systems (Douglas, 2020) and the management of the Marine Maker CAD file repository (Audette, 2019).

As seen in Figures 14 and 15, respectively, the TACFAB and XFAB offer varying levels of organizational and intermediate-level AM support in austere or remote locations.

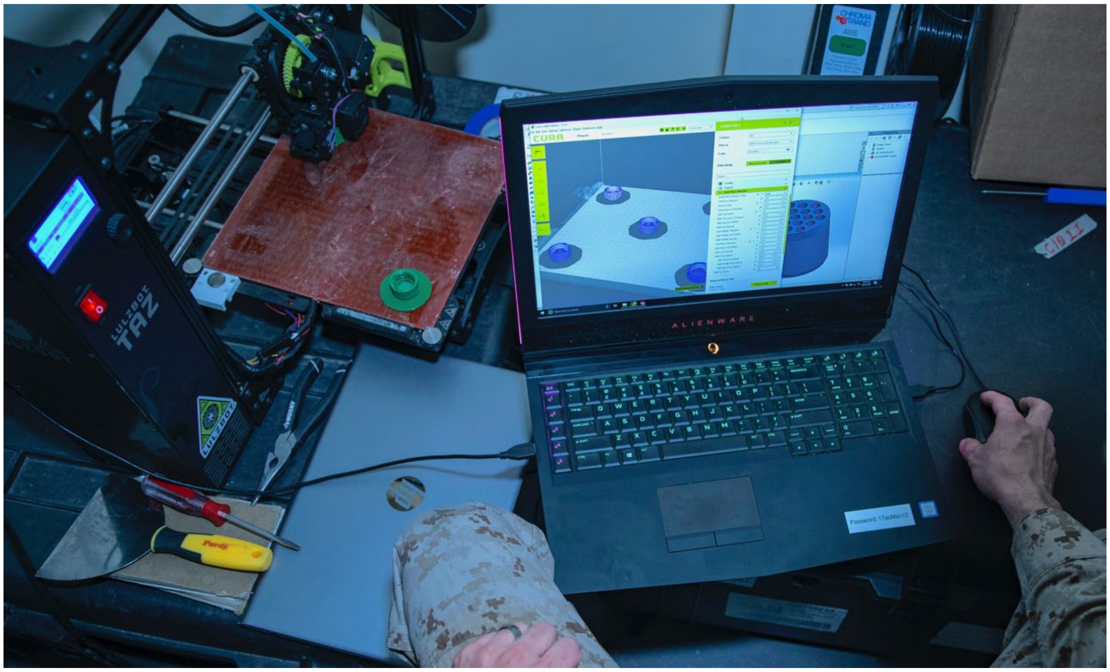

Figure 14. LulzBot TAZ 6 3D Printer (TACFAB). Source: Fuentes (2019).

Figure 15. XFAB Expandable Shelter. Source: Randolph (2017).

For the USS *Murtha* and USS *Boxer* deployment in 2019, the LulzBot TAZ 6 3D printer served as the TACFAB (Fuentes, 2019). The XFAB is similar in design to other Marine Corps expandable shelters, and when fully expanded it measures 20 feet by 20 feet and weighs 10,500 pounds. The system is designed to be set up by a team of four Marines, taking between 2 to 3 hours. This system will house several 3D printers, a scanner, and a CAD software system to create not only physical items but create and provide CAD files in remote environments (Randolph, 2017). Also, the Marine Corps is pursuing to make the TACFAB and XFAB POR in FY2019 and FY2020 (Douglas, 2020). The TACFAB's design, depicted in Figure 14, is not finalized. The XFAB design will be identical or similar to the one depicted in Figure 15. Once both designs are finalized, initial fielding is scheduled for FY2021 with 17 XFABs and 169 TACFAB systems being delivered throughout the Marine Corps (Douglas, 2020).

The other initiative the AMOC cell is pursing is the expansion of the Marine Maker CAD file repository. This website is open facing to the World Wide Web and allows for username and password access to those users with accounts. These accounts require a military or DOD email to authenticate. The website does not require the usage of a Common Access Card (CAC) for ease of use for those Marines not on a Marine Corps or DOD network. The Marine Maker portal does replicate with the JAMMEX repository (Douglas, 2020). However, as of January 2020, the repository "cannot handle the volume of data currently stored" (Douglas, 2020, p. 8), and the AMOC is pursuing another digital repository called the Digital Manufacturing Data Vault (DMDV) to handle the large quantities of files (Audette, 2019) with that repository becoming a POR in FY2024 or FY2025 (Douglas, 2020).

The civilian and international community, the DOD and the DON, and the Marine Corps have taken great strides to increase the capacity of AM in their respective organizations and to extend the influence AM can have beyond maintenance support. AM is not a new technology. "It has evolved from an interesting hobby to an industry producing a wide range of products from an ever-growing list of materials" (Hammes, 2017, p. 101). All of the previously mentioned literature and initiatives in this chapter have had and will continue to have significant impacts on how the Marine Corps incorporates AM. MCO

4700.4 has replaced the aforementioned MARADMINs to be the focal source of AM knowledge and guidance in the Marine Corps. As such, further reviews of this order must take into account the previously mentioned literature and initiatives to truly capture the benefits of AM in the Marine Corps.

D. MCO 4700.4 REVIEW

MCO 4700.4 was signed in March 2020. This document's goal was to align with the DOD's interim policy of 2019 and the DON's implementation plan of 2017. The order was to replace previous MARADMINs discussing AM integration and expand upon the framework those documents had established—with the exception of MARADMIN 209/18, as that document applies specifically to air assets and AM integration. The order is broken into two parts, the operational order (OPORD) and two enclosures. The OPORD follows the traditional format of situation, mission, execution, administration and logistics, and command and signal (SMEAC). The two enclosures include (a) a list of references and (b) six chapters addressing the integration of AM. The chapters are introduction, implementation, manufacturing process, aviation, legal considerations, and training. This research does not seek to address the validity of the structure of the order, but the researcher concurs that it follows similar Marine Corps orders, which provides familiarity to the intended audience of Marine Corps officers and enlisted Marines.

As stated, the first part of the order is formatted using the SMEAC model. The situation section highlights two key elements. First, it states, "AM is a secondary source of supply that improves equipment readiness through production at the point of need" (DC I&L, 2020, p. 1). This point emphasizes that AM will augment—not replace—traditional manufacturing, and AM is an effort to place more logistics capabilities at the point of need. Second, this chapter acknowledges the previously mentioned guidance from the DOD and the DON as source documents. The mission section is traditionally the "heart" of any order and this order is no exception. The mission statement reads, "Commanders at all levels shall employ and develop additive manufacturing to its fullest extent possible in order to improve combat readiness in garrison and during expeditionary operations" (DC I&L, 2020, p. 1). The part of the mission statement regarding commanders at all levels highlights the drive for a bottom-up approach, as seen in Table 7's Goal #3 (Douglas, 2020). The last part of the mission statement regarding expeditionary operations highlights Table 7's Goal #1 of conducting manufacturing at the point of need (Douglas, 2020). Following the situation and mission section is the execution section, which traditionally is the largest part of any OPORD.

The execution section is broken into two parts. First is the commander's intent and concept of operations, and second is the tasking statements. Commander's intent and concept of operations further expands upon the previously mentioned mission statement, while the tasking statements of this section specifically name individuals or organizations and assign them specific tasks. For commander's intent, the intent is "to reduce maintenance cycle times, supply chain backlogs, and place manufacturing capabilities at or near the point of need" (DC I&L, 2020, p. 1). For the concept of operations, the focus is for commanders at all levels to create a "'Marine Maker' culture" (DC I&L, 2020, p. 2), which seeks to receive AM input from all Marines and military occupational specialties (MOS). This maker culture in warfare is not the first time in history that Soldiers have fabricated and manufactured in austere and remote environments. The Roman legionnaires were just as effective warriors as they were manufacturers, which allowed them a strategic advantage against the far larger-numbering Gallic foes in the conquest of modern-day France (Carlin, 2017). As Marines continue to fight abroad, this capability and mindset has again strategic implications for the Marine Corps' future success against foes that outnumber the Marine Corps.

The tasking statements include 10 people and organizations that are involved in AM integration. However, five are critical stakeholders in this research. First, DC I&L tasks themselves or, more importantly, their staff with the following tasks. They need to serve as the AM lead in the Marine Corps but task a separate entity to serve as the lead agent who at the time of this order is the AMOC. Also, DC I&L again tasks themselves to be the Marine Corps advocate and participant in all joint initiatives such as the JAMSG and Navy Additive Manufacturing Executive Committee to ensure that Marine Corps policies are aligned with higher headquarters guidance. This taskings allow DC I&L and their staff to be the outward face for AM for the Marine Corps, while the lead agent can work internally and downward into the Marine Corps to provide guidance and direction. This duality between DC I&L and MCSC (through the AMOC) will create clear roles and responsibilities for both organizations. Second, Deputy Commandant, Combat Development and Integration (DC CD&I) is tasked with ensuring that Total Force Structure Management System (TFSMS) data contains accurate information on units' AM equipment inventory. The TFSMS portal stores all Marine Corps units' tables of organization (TO) and tables of equipment (TE). The TO is not a personnel tracker. This document contains a list of all Marine Corps billets that a unit is authorized to have and not which individual Marines make up the unit. The TE is similar to the TO, but it lists all the equipment a unit rates instead of what the unit actually has on hand. Third, Deputy Commandant, Information (DC I) is tasked with cybersecurity. This order specifies that those cybersecurity tasks are to develop an authority to operate (ATO) for AM assets on the Marine Corps Enterprise Network (MCEN), develop a standardized format for the acquisitions of AM hardware and software, support MCSC with the digital repository and its security, and—in conjunction with Marine Corps Installations Command (MCICOM)—ensure appropriate funding to allocate network infrastructure in support of AM efforts. The only specific cybersecurity statement or reference came with the two words of "security measures" (DC I&L, 2020, p. 3). Fourth, MCSC serves as the lead agent and "technical authority for all ground applications of AM" (DC I&L, 2020, p. 4). This includes the creation and management of the digital repository that must also integrate with other military services, DLA, and North Atlantic Treaty Organization (NATO) repositories. Fifth, TECOM reviews all entry-level training programs and sustainment courses to integrate AM training throughout the Marine Corps. As for the last two sections of the OPORD and the first enclosure, they are administrative in nature and not necessarily vital to this research.

Following the OPORD and list of references, the second enclosure provides AM policy and is broken into six chapters with the first being the introduction. The introduction highlights the current logistics issues facing Marine Corps units such as long lead times, expensive repair parts, obsolescence of gear or lack of OEMs, and the inability to rapidly adapt to evolving threats on the battlefield. The introduction then goes on to state that AM could mitigate or remove these logistical problems. The introduction also provides definitions as well as varying types of 3DP options to provide a baseline for all Marines to mitigate misinterpretation between different units and organizations in the collaboration of AM across the Marine Corps.

The next section of the introductory chapter states the four levels of AM operations. First, *organizational operations* are the lowest level and are placed at battalions or squadrons operating in austere and remote locations. These units are fielded the TACFAB to provide organic, point of need, polymer fabrication. Second, *intermediate level operations* are conducted with traditional intermediate maintenance activity (IMA) units, such as maintenance battalions, where trained machinists operate the XFAB system. The XFAB can provide polymer and limited metal fabrication capabilities. *Depot level operations* serve as the highest tier of operational AM activities and are organic to Marine Corps Logistics Command (LOGCOM). This AM capability provides fabrication of specialized polymers, specialized metal alloys, and other unique materials. Fourth, *installation operations* serve as the garrison capability in support of the three other operational levels. This level contains the Marine Maker spaces, and these spaces are placed aboard Marine Corps bases and installations where appropriate. This level of operations also provides an educational component with trained personnel staffing the Marine Maker spaces to further foster an innovate and adaptive culture with which Marines can test new concepts and ideas for AM application. Finally, these Marine Maker spaces have "computerized numerical controlled (CNC) mills/routers, water jets, laser cutters, microcontrollers, and electronic sensors" (DC I&L, 2020, p. 1-4) to assist in the innovate ideas and concepts from all Marines.

The introductory chapter also provides a brief description of construction-scale additive manufacturing (CSAM), discussing AM manufacturing with concrete as seen in Exercise Burgeon Strike. However, this subsection of the introductory chapter provides only an overview of this capability and not specific recommendations or resources for the employment of CSAM as the Jagoda et al. (2020) article provided.

The last subsection of this chapter addresses AM machines on the MCEN and the digital repository. First, this last subsection states that AM machines are not authorized on the MCEN, which has impeded AM integration. Furthermore, the order states that AM machines are similar to multifunction devices (MFD), which already have an ATO, thus AM machines should easily receive an ATO approval rating. An example of an MFD currently approved for the MCEN is a copier, printer, scanner machine. However, as seen in the research of Zeltmann et al. (2016), if a 3D printer changes the direction of its printing, it will have significant impacts on the quality of the printed item. Conversely, if a traditional paper print changes direction, the print quality will remain the same. Thus, the orders claim of AM printers and MFDs being similar is inaccurate and could lead to unnecessary assumed risks. Furthermore, this subsection ends with the uniform resource locator (URL) for both the ground and aviation repositories.

Chapter 2 discusses the implementation of AM at an enterprise level as well as a ground- and aviation-specific level. Similar to the tasking statements in the SMEAC order, tasking statements are used for implementation guidance. For the enterprise-level tasks, they are separated by functional areas instead of by people and organizations. Once the order begins to discuss the ground- and aviation-specific tasks, those tasks are broken down by people and organizations as seen in the SMEAC order. Thus, this entire order has three different sections covering tasks, which are broken into two different formats.

The enterprise-level tasks have four functional areas. First, the policy functional area discusses the memorandum of understanding (MOU) between all the Marine Corps organizations involved with AM and tasks MCSC as the lead agent through the AMOC. It also states that DC I&L will lead any edits and revisions to this order. Second, the training functional area tasks DC CD&I with creating training programs for entry level as well as sustainment programs even though earlier TECOM was tasked. Also, TECOM is not mentioned as a support effort either in this portion of the order. Though DC CD&I and TECOM are different organizations, they both have an overlapping responsibility for the training and education of AM in the Marine Corps. Third, the resourcing functional area discusses the building of Marine Maker spaces led by DC I&L and the management of the digital repository lead by MCSC. It does state that the current repository will be replaced by the DMDV as a POR in FY2021. Also, this digital repository must replicate with other military services and coalition partners. Finally, the order includes tasks for MCSC to increase the accessibility of AM software on the MCEN and identifies DC I as a supporting entity—not the lead. Fourth, the last functional area is legal considerations. Though important, this research does not focus on the legal considerations of AM, as other research has been conducted to address this topic.

Following the enterprise-level tasks, the ground-specific tasks address all key stakeholders and their responsibilities. This list duplicates some of the tasks mentioned under the execution section of the OPORD but primarily expands upon the role of MCSC. The tasks reiterate the importance of the digital repository and standardization of AM systems such as the TACFAB and XFAB. However, the order discussed MCSC's and the AMOC's expanded roles in three key areas. First, the AMOC must establish a 24-hour help desk to respond to AM queries. Second, the AMOC must develop a prototyping lab to test and validate designs from Marine Corps units. Third, the AMOC must establish relationships with civilian industries to expand Marine Corps AM capabilities and capacities. With this expanded role defined and the MOU established, MCSC through the AMOC is positioned to effectively lead AM efforts within the Marine Corps.

Chapter 3 addresses the manufacturing process. It discusses what items each level of operations can and cannot print as well as the role of getting CAD files approved. As the level increases so too does the ability to create and print more parts of varying materials. This order specifically and effectively addresses each level's authorities. This chapter then discusses in detail the approval process for CAD files as depicted in Figure 16.

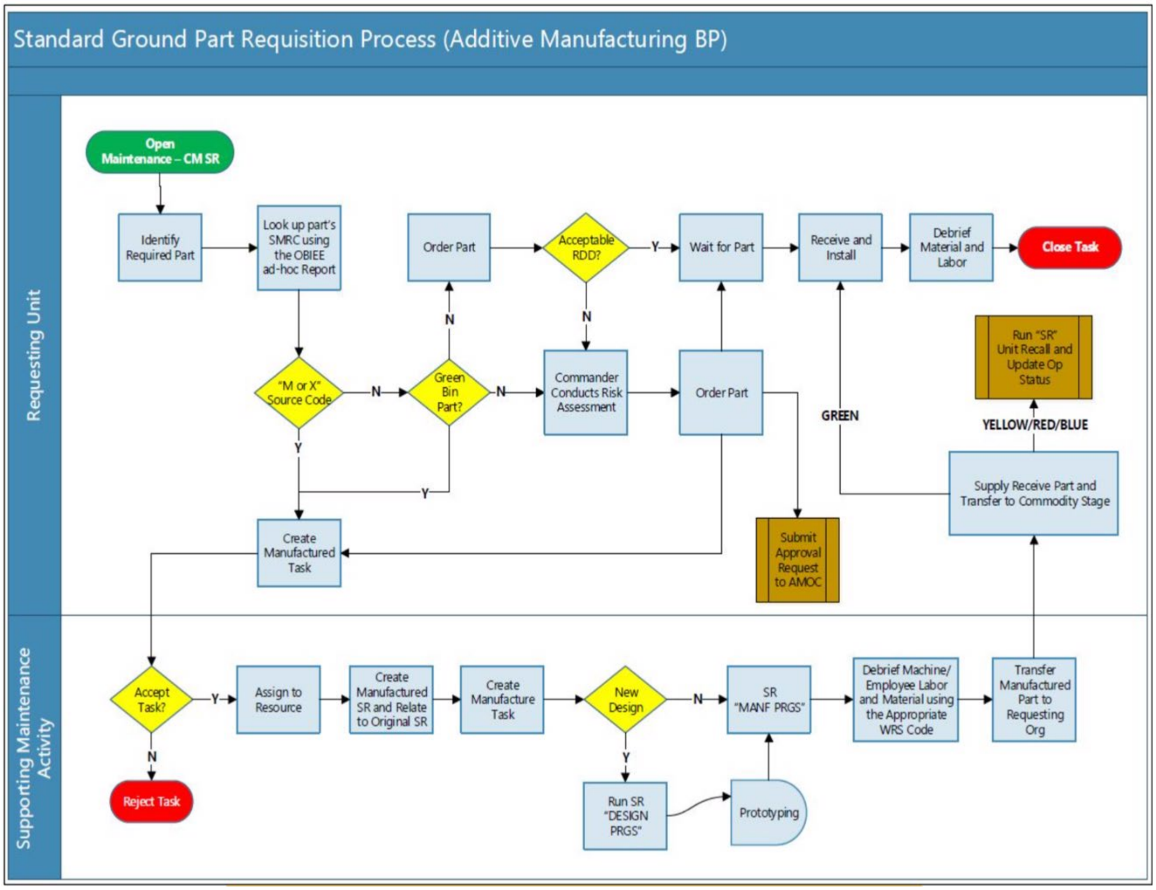

Figure 16. Marine Corps CAD File Approval Process. Source: DC I&L (2020).

The approval process also discusses in detail the categorization of CAD files into bins by color and outlines who is authorized to print from each bin. Green bin files are those approved for printing and can be printed by any organization with the appropriate AM system and materials. Yellow bin files are those in the initial design stage and have not yet been submitted in the formal approval process to the AMOC. Blue bin files are similar to yellow bin files with the exception that the file has now entered the formal approval process with the AMOC. Red bin files are those determined not authorized for printing. The order does specify that all files, including even red bin files, can be printed by the appropriate level command if the risk is deemed sufficient in supporting the operational need. The last part of this chapter discusses the labeling and filing of CAD files for ease of tracking and documentation.

Chapter 6 is the final chapter of the policy and discusses the training considerations for AM. Chapters 4 and 5 discuss aviation and legal considerations, respectively, which—although important—are not the focus of this research. Chapter 6 discusses the four levels of training as seen in Table 8. This chapter again highlights the importance that TECOM will have in incorporating training both in entry-level and sustainment courses for Marines of all MOSs and not just machinists.

Table 8. MCO 4700.4 Levels of Training. Source: DC I&L (2020).

Training Level	Description
Familiarization Training	Introductory awareness training for all hands consisting of AM capabilities and program familiarization.
Level 1: Operator	Level 1 training consists of teaching Marines to operate printing equipment and print approved items.
Level 2: Incidental Programmer	Level 2 training consists of CAD, operation of a slicer program, printing noncritical materials, performing basic maintenance on printing equipment, and submitting technical data for approval.
Level 3: Formally Trained	Level 3 training consists of advanced CAD programming, reverse engineering, structural analysis, equipment maintenance, and material selection.

MCO 4700.4 took DOD and DON guidance to formally provide the entire Marine Corps with the guidance and policy for implementing AM in their respective units and organizations. The chapter regarding the manufacturing process went into specific and effective guidance on how to create and approve CAD files. Furthermore, the training chapter and philosophy of focusing on all Marines not just a select few is another proactive and sound decision. Certain areas can be expanded upon such as the TACFAB being more expeditionary as well as a tailoring of the tasking statements. Those areas are relatively minor and easier to address. However, a larger concern is the lack of a robust cybersecurity plan. This lack of cybersecurity offers vulnerabilities for adversaries to exploit and mitigate the benefits AM can offer the Marine Corps.

IV. DATA ANALYSIS AND CONCLUSION

MCO 4700.4's guidance attempts to empower all Marines and their commanders to integrate AM as a secondary source of supply. In achieving this primary objective, MCO 4700.4 appears to achieve this objective. The order seeks to partner with civilian and international partners as well as align with published guidance from the DOD and the DON. Furthermore, the order seeks to expand upon the achievements of prior Marine Corps initiatives instead of acting as a replacement. Even though the order does achieve its primary objective, areas can be improved or expanded to further assist those commanders and Marines in more effectively integrating AM into their routine operations. The first subsection of this chapter addresses the primary research question: *What is additive manufacturing's current position within the Marine Corps and what areas could be improved?* The next two sections cover the subsequent two secondary research questions. First, *What unique risks does AM present to the Marine Corps?* Second, *What specific opportunities does AM provide the Marine Corps that they are not pursuing or are not pursuing to their fullest extent?*

One analytical tool that this research uses to assist in the analysis of the data when compared to the research questions is a report card–style rubric. As depicted in Table 9, the color format is similar to Slate's (2004) discussion on grading contractors during source selection. The overall objective of this analysis is for decision-makers to incorporate this analysis and the conclusions into the next revision of MCO 4700.4.

Table 9. Grading Rubric. Source: Slate (2004).

Grade Description	Grade Color
Exceptional	
Acceptable	
Marginal	
Unacceptable	

A. WHAT IS ADDITIVE MANUFACTURING'S CURRENT POSITION WITHIN THE MARINE CORPS, AND WHAT AREAS COULD BE IMPROVED?

On March 23, 2020, MCO 4700.4 became the source document for AM policy for ground equipment. It transitioned the Marine Corps from official message traffic through MARADMINS to official AM policy. In the absence of thorough guidance from the DOD, the Marine Corps has effectively taken initial steps to properly integrate AM. Several areas throughout the order demonstrate a programmatic approach to AM by driving down cost, decreasing time requirements, and increasing performance while also reducing risk to an acceptable level for on-site commanders to make AM decisions. First, the cultural undertone of MCO 4700.4 emphasizes the need for a bottoms-up approach that is led by the next generation of Marines to truly make every Marine a "maker" of supply items that are necessary for mission accomplishment. Second, risk is placed on the lowest level commander instead of decision-makers in the National Capital Region. Third, AM education and training opportunities will not only inspire all Marines, but also synchronize efforts across the Marine Corps by establishing an AM training baseline. Fourth, the bin system of AM CAD files allows for flexibility in the adoption of AM technology. Fifth, the tiered approach of organizational, intermediate, depot, and installation levels for AM equipment places AM not only at the point of need, but throughout the supply chain. Finally, the XFAB and TACFAB systems allow for tailored solutions to operational requirements.

1. Cultural Undertone of MCO 4700.4

MCO 4700.4's mission statement calls for commanders at all levels to create a "'Marine Maker' culture" (DC I&L, 2020, p. 2) within their organizations. The order seeks to inspire Marines of all ranks and MOSs to be a maker. If harnessed properly, this new ability will make the Marine Corps a more lethal force by placing "production at the point of need" (DC I&L, 2020, p. 1). The order is not seeking AM to replace other systems but to augment established logistics and supply systems to increase the Marine Corps' lethality. Other examples of this cultural undertone exist with the creation of Marine Maker spaces and with driving a bottoms-up approach to AM implementation instead of the traditional centralized and downward control. This maker culture in warfare is not the first time in history that Soldiers would fabricate and manufacture in austere and remote environments. The Roman legionnaires were just as effective warriors as they were manufacturers, which allowed them a strategic advantage against the far larger-numbering Gallic foes in the conquest of modern-day France (Carlin, 2017). As Marines continue to fight abroad, this capability and mindset has again strategic implications for the Marine Corps' future success against foes that outnumber the Marine Corps. This cultural shift is the most important aspect of AM integration, which—it appears—the Marine Corps has effectively grasped and disseminated to all Marines.

2. MCO 4700.4: Risk Tolerance Vice Risk Avoidance

Another cultural shift is placing the responsibility or risk of AM production with battalion and regimental-level commanders. Even though the mission statement specifically identifies "commanders at all levels" (DC I&L, 2020, p. 1), the fact that it did not exclude those battalion and regimental commanders is significant. This significance is further evident in allowing those commanders to produce any item, including red bin items that have been deemed unfit by the AMOC, if the operational impacts outweigh the risks of printing the item. Placing this risk decision on the on-site commander will more likely inspire all commanders to implement this new technology as they have more influence on the process with this decision-making capability. Having a risk tolerant and risk mitigating culture instead of a risk avoidant culture is key to effectively adopting any new technology, and AM is no exception.

3. AM Education and Training

In conjunction with risk tolerance, the drive for thorough AM educational programs shows the dedication the Marine Corps has to adopting AM throughout the entire force. MCO 4700.4 presents a detailed and tiered approach to education. Also, with the creation of Marine Maker spaces, these spaces will support the cultural change of making every Marine a maker and truly try to indoctrinate, instead of just simply using this new technology. The Marine Corps also plans to create an additional military occupational specialty (AMOS) for AM in FY2022 (Douglas, 2020). This will first incentive Marines to educate themselves, as attaining AMOSs makes Marines more competitive for promotion. Second, Marines with AMOSs instead of just training certificates are easier to identify in Marine Corps administrative and manning repositories such as Marine Online and Command Profile. This identification will allow all leaders, not just the specific Marine's immediate supervisor, access to which Marine Corps units have AM-trained Marines. Furthermore, this identification can be paired with a unit's TO to help determine which units require AM-trained Marines and prioritize those units for training.

4. MCO 4700.4's CAD File Bin System

The bin system for AM parts allows for increased operational flexibility. The bin system of identifying AM parts for printing by green, yellow, blue, and red allows not only the AMOC to broadcast the status of CAD files, but it also helps commanders identify risks immediately. For example, if an operation dictates the printing of an item that is not green, the commander can easily make a risk-based decision based on the color identification and the situation on-site. If the item is blue, the commander might deem it worth printing rather than if the item were red. Thus, commanders can make informed risk-based decisions on all items—not just decisions based on a red or not red status.

5. MCO 4700.4's Equipment Tiers

In conjunction with the bin system flexibility, the tiered approach to AM equipment implementation offers increased flexibility and other advantages to the Marine Corps. It captures the advantages of both a centralized and distributed AM implementation as Boer (2020) and his team discussed. Centralized AM manufacturing can be seen at the intermediate and depot levels by providing a robust AM suite of equipment that focuses on the production of items with a below-average demand and long manufacturing lead times (Boer et al., 2020). Distributed AM manufacturing can be seen at the organizational and intermediate levels by providing forward printing at or close to the point of need for those items with an unpredictable demand and short manufacturing lead times (Boer et al., 2020). The intermediate level contains both centralized and decentralized aspects with the design of the XFAB. Even though the XFAB comes with a suite of printers as well as computers and servers for CAD file creation and management, which serve in a more central role, the expandable shelter is still a mobile asset that can more easily maneuver in a operational environment than other more permanent structures. The XFAB does not achieve the mobility of the TACFAB or the robust capabilities of a depot but seeks to achieve both capability and mobility. In conjunction with the organizational and depot level, this blending of both a centralized and distributed AM process provides tailored packages for the Marine Corps to apply to a wide range of military operations.

As evident in the tiered approach, the XFAB and TACFAB have effectively integrated AM technology into Marine Corps operational needs. The Marine Corps operates in diverse environments and operational situations. One system cannot adequately fulfill all the requirements for Marine Corps units operating in the multitude of diverse situations. Thus, different systems mirrored to the tiered approach seek to offer on-site commanders with the flexibility to adopt various AM equipment postures to best manage the operational environment. The XFAB system is an expandable shelter with multiple 3D printers inside. The TACFAB system is comprised of the LulzBot TAZ 6 3D printer. As a system's concept, the XFAB and TACFAB perform well in both kinetic and nonkinetic environments. However, only the XFAB's expandable shelter performed well in both environments. The TACFAB's LulzBot TAZ 6 3D printer does not possess the same capabilities as other similar printers such as the Kijenzi discussed by Savonen and his team (2018). Therefore, the LulzBot printer, not the TACFAB concept, is a limiting factor; replacing the LulzBot printer could potentially address performance issues in austere environments without the need to replace the entirety of the TACFAB concept.

As depicted in Tables 10 and 11, the printer requirements and design characteristics Savonen and his team discussed are used to grade the XFAB expandable shelter, the TACFAB's LulzBot TAZ 6 3D printer, and the Kijenzi 3D printer. This research is not grading the TACFAB concept but the LulzBot TAZ 6 3D Printer.

Table 10. XFAB, LulzBot, and Kijenzi Grades for Savonen's Printer Requirements. Adapted from Savonen et al. (2018), Slate (2004).

Requirements	XFAB	LulzBot	Kijenzi
The 3D printer must be able to make useful parts.			
The 3D printer must be able to function independent of infrastructure.			
The 3D printer must be able to be easily transported.			
The 3D printer must be safe and easy to use.			
The 3D printer must be able to withstand harsh environments.			
The 3D printer must be able to be procured for minimal cost.			

For printer requirements, the XFAB and Kijenzi printer perform far better than the LulzBot. For printing useful parts, the XFAB trailer far exceeds the others, as it can print both polymer and metal items with both AM and hybrid manufacturing techniques. For infrastructure requirements, all can operate autonomously, but the XFAB and LulzBot will require nonsolar energy to operate. This fuel type limitation means the XFAB and LulzBot require a fuel source to be transported throughout the host nation. For transportability, the Kijenzi far exceeds the others by being transportable in two large duffel bags. Even though the XFAB trailer is far larger and heavier than the other two printers; however, when accounting for the relative capabilities that the XFAB provides, it still is relatively able to be transported. For safety and ease of use, all three printers are safe and easy to use. For handling harsh environments, the XFAB is a hardened trailer that can withstand various environments, while the Kijenzi is a ruggedized 3D printer. The LulzBot, however, was not designed for use in a harsh environment and requires shelter from the elements for operation. For cost, the XFAB is the most expensive by far. However, similar to the transportability grading, it still receives a marginal grade when accounting for the capabilities it offers. According to the LulzBot webpage, that printer costs $2,500 (LulzBot, 2020), while the Kijenzi only costs $776.28 (Savonen et al., 2018).

Again, this research does not seek to demonstrate that the TACFAB concept is ill-suited for Marine Corps operations. Rather, this research seeks to demonstrate that other printers besides the LulzBot TAZ 6 3D printer exist that are potentially better to be fielded within the TACFAB system.

Table 11. XFAB, LulzBot, and Kijenzi Grades for Savonen's Printer Design Characteristics. Adapted from Savonen et al. (2018), Slate (2004).

Design Characteristics	XFAB	LulzBot	Kijenzi
Fused Filament Fabrication (FFF)			
Open-Source RepRap Design			
Modular Design			
Separable Frame			
Protected Electronics			
On-Board Computer System			
Flexible Power Supply			
Climate Control Mechanisms			

For design characteristics, the XFAB and Kijenzi printer again perform far better than the LulzBot. For FFF, all printers are capable of this fabrication, but the XFAB scored higher, as it can manufacture a far wider variety of items with various materials and techniques. Open-Source RepRap Design was not used as a grading metric, as RepRap is a civilian project to increase interoperability of printers with partner nations in the civilian RepRap initiative (Savonen et al., 2018). For modular design, the XFAB has the most modularity inside the expandable trailer, while the Kijenzi does offer modularity for follow-on expansion. However, the LulzBot is a fairly closed system that does not offer much in the way of future expansion. For separable frame, the XFAB is not able to be broken down into separate parts for transport; however, with it being an expandable shelter, the XFAB does offer some of the same benefits of a separable frame when taking its robust capabilities into consideration. The Kijenzi offers the most benefit in a separable frame for ease of transport. For protected electronics, the XFAB offers the most protection with a hardened structure, while the LulzBot offers little to no protection for its electronics and requires other structures to protect it during printing. For on-board computer system, all three systems have an on-board computer; however, the XFAB allows for storage of CAD file servers and CAD file creation to a scale that the other two systems do not provide. For flexible power supply, the Kijenzi offers the most flexibility with the ability to use solar power as well as traditional energy sources. Finally, only the XFAB and Kijenzi offer a climate control mechanism while the LulzBot does not. This grading demonstrates that the XFAB and Kijenzi exceed expectations in several design areas while achieving at least minimal scores in all other requirements and design characteristics, while the LulzBot printer is either meeting marginal standards or not meeting standards at all.

MCO 4700.4 provides the programmatic baseline upon which the Marine Corps can provide a deliberate and synchronized path forward in further integrating and expanding AM capabilities for the entire force. Overall, the document serves the Marine Corps well in covering the previously mentioned sections. Furthermore, the document does address, at a minimum indirectly, the decreasing of total ownership costs for Marine Corps systems, more timely delivery of capabilities to the warfighter, and increased performance to the warfighter. Finally, it adequately addresses risk to ensure that leaders can make risk-tolerant decisions to achieve the greatest benefit while diminish risk to appropriate levels. Even though risk decisions are addressed within the document, other areas or a lack of other areas does present some overarching programmatic risk to the adoption of AM into the Marine Corps.

B. WHAT UNIQUE RISKS DOES AM PRESENT TO THE MARINE CORPS?

The most significant risk to AM, which is not adequately captured in MCO 4700.4, is the lack of a robust cybersecurity plan. This research does not seek to say that cybersecurity is not considered nor that other documents were created that are not available to the general public. For the latter point, it makes sense to keep such documents under stricter distribution as to not provide adversaries with the plans for how to specifically secure the AM cybersecurity posture. However, certain elements of MCO 4700.4 indicate either a lack of a cybersecurity plan or provide an inadequate cybersecurity plan at best. This subsection initially provides an overview of the risk Risk Management Framework (RMF) and, in particular, the three key elements to safeguard, which are confidentiality, integrity, and availability (CIA) of data. Then, this research analyzes those elements of cybersecurity that present either unnecessary or needlessly high risk. Finally, analysis is conducted on how to either remove or mitigate the previously mentioned risk.

1. RMF Overview

The Department of Commerce's (DOC) Federal Information Processing Standards (FIPS) Publication 199 and National Institute of Standards and Technology (NIST) Special Publication 800-60 Volume I describe both the definitions of CIA and the RMF process, respectively. Figure 17 depicts the definitions of CIA and their impacts if comprised. Figure 18 depicts the six-step RMF process.

	POTENTIAL IMPACT		
Security Objective	**LOW**	**MODERATE**	**HIGH**
Confidentiality Preserving authorized restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. [44 U.S.C., SEC. 3542]	The unauthorized disclosure of information could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized disclosure of information could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized disclosure of information could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.
Integrity Guarding against improper information modification or destruction, and includes ensuring information non-repudiation and authenticity. [44 U.S.C., SEC. 3542]	The unauthorized modification or destruction of information could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized modification or destruction of information could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The unauthorized modification or destruction of information could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.
Availability Ensuring timely and reliable access to and use of information. [44 U.S.C., SEC. 3542]	The disruption of access to or use of information or an information system could be expected to have a **limited** adverse effect on organizational operations, organizational assets, or individuals.	The disruption of access to or use of information or an information system could be expected to have a **serious** adverse effect on organizational operations, organizational assets, or individuals.	The disruption of access to or use of information or an information system could be expected to have a **severe or catastrophic** adverse effect on organizational operations, organizational assets, or individuals.

Figure 17. Confidentiality, Integrity, and Availability Definitions and Impacts. Source: Department of Commerce (2004).

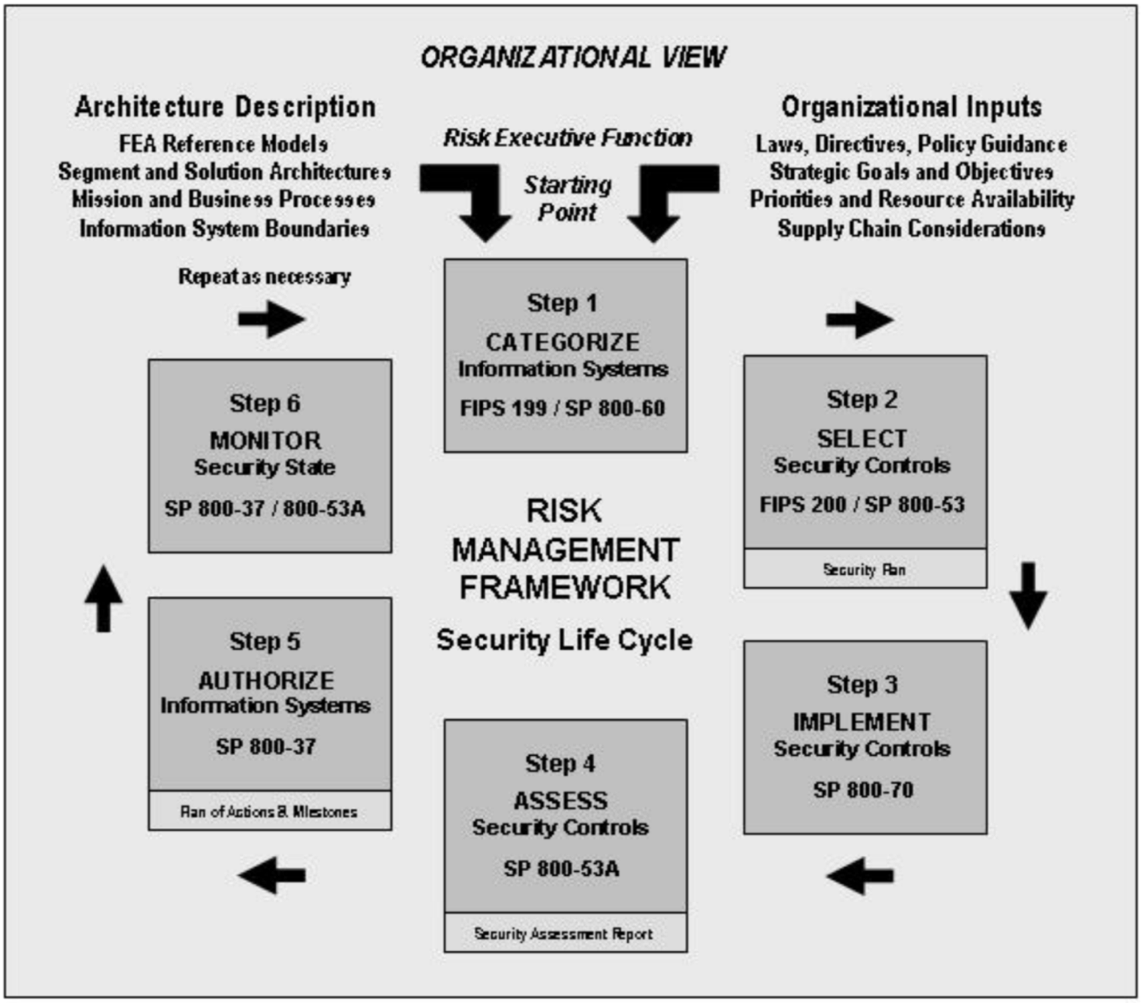

Figure 18. Risk Management Framework Overview
Source: Department of Commerce (2008).

The key RMF step for this research is Step 1, Categorize. This step is the categorization of a system with regard to the three criteria discussed in Figure 17. For example, if a system were deemed to have a high confidentiality rating, then the impact to having its confidentiality comprised would be a severe or catastrophic impact, while if it only had a low confidentiality rating then the impact would be limited. As MCO 4700.4 implies that the 3D printers are not yet authorized for access to the MCEN and a new digital repository (which replicates with JAMMEX) will be replacing the current digital repository, time is available to categorize and correct any cybersecurity deficiencies. This research conducts an abbreviated form of Step 1 to demonstrate the impact that a lack of robust cybersecurity can have on AM implementation.

2. RMF Categorization Example #1

The first example is the categorization of 3D printers on the MCEN. As the Zeltmann article discussed, changing the files to insert weak points as well as changing just the direction of the printer can have severe effects on the print and resulting item quality (Zeltmann et al., 2016). However, basic knowledge of these printers—such as schematics, printer speed, printer quality, and other such technical aspects—is readily available on the internet. Thus, adversaries having this basic information of the printers is not a threat. With the understanding that this information is readily available to everyone, confidentiality would be rated with a low impact. However, integrity would be rated with a high impact grading, as affecting print quality and printer direction has a severe impact (Zeltmann et al., 2016).

Furthermore, as having access to these printers is paramount to receiving printed items, an attack on a printer's availability would be severe. However, adversaries need to have physical access to these printers as they are not connected to the internet as of MCO 4700.4's publication to effectively target their availability. When grading the availability of the entire inventory of printers but only removing the availability of a few printers, the availability grading of the entire inventory would decrease to a serious or moderate impact. This grading changes, though, when considering MCO 4700.4's objective of connecting these printers to the internet. When these printers connect to the internet, adversaries can target the entire inventory and from a remote location. As MCO 4700.4 desires to connect these printers to the internet, this research will grade availability under that objective. Thus, printer availability with a connection to the internet would have a severe or high impact, as adversaries can target the entirety of the printer inventory and stop them from being able to print items.

To conclude, these printers have a low impact rating for confidentiality, a high impact rating for integrity, and a high impact rating for availability if connected to the internet. Therefore, the primary objectives of cybersecurity efforts and controls are twofold. First, safeguards must be implemented to protect the printer's integrity against adversaries' destructive modification or alteration of the printers. Second, safeguards must also protect against the ability to remove the availability of the entire inventory of printers. Risk-based decision-making should be conducted to weigh both the benefits and problems with connecting these printers to any network.

3. RMF Categorization Example #2

The second example is the categorization of any digital repository for the Marine Corps CAD files. This research assumes that this digital repository of CAD files will also store the location of AM equipment as recommended in the 2019 DODIG report. The location of AM equipment is vital information for not only Marine Corps forces but for adversaries as well. However, knowing the location of an AM printer would only have serious implications if follow-on adversarial actions were to occur to make the situation severe or catastrophic. Therefore, confidentiality would be ranked moderate. As previously stated, minor alterations to files can have significant impacts to the printed items' quality. Therefore, integrity is again rated high due to the severe impacts a breach of integrity would have on CAD files. Finally, availability of the website is critical for Marines to print files. This could be mitigated with the creation of local servers that replicate the central database, but the removal of the digital repository would still have severe implications. Thus, availability would be graded high. To conclude, the digital repository would have a moderate impact grading for confidentiality, but a high impact grading for integrity and availability. Cybersecurity efforts should prioritize this digital repository first before proceeding to put the printers on the network, as more areas of CIA are rated higher for the digital repository than for placing the printers on the network.

4. Future RMF Implementation

As the digital repository has far larger cybersecurity impacts if compromised, actions must be immediately taken to safeguard against adversarial actions. First, the current digital repository is open facing to the World Wide Web and only requires username and password authentication. Second, MCO 4700.4 contains the URL for this website, and MCO 4700.4 can be found relatively quickly with a simple online search.

Third, the order places cybersecurity responsibility with MCSC and with DC I as a supporting role, but the order does not mandate the usage of the RMF process or discuss other specific steps to help safeguard against adversarial cyber threats. However, simple and quick actions can be taken to mitigate these three issues.

First, the next digital repository must require CAC authentication for both account creation and ongoing access. Another step to further shield against adversarial attacks would be to implement two-factor authentication. This last step might compromise availability of the system for those Marines in remote locations and without adequate cell phone service. Other two-factor authentication measures are available besides cell phones, but again two-factor authentication might not be necessary if CAC authentication is deemed sufficient to mitigate against the risk of unauthorized access and manipulation of the data. Second, the next digital repository must only be accessible on a government machine. This would mitigate against denial of service attacks or easy location of the website. Also, printing the location of the digital repository would no longer be as a significant of an issue if the site could only be accessed from a U.S. government machine. Finally, if DC I is actively engaged and supporting MCSC and the AMOC in the creation of a robust cybersecurity plan, then no issue exists in this third category. However, the research indicates that this collaboration is not happening when statements are issued such as, "3D printers are similar to MFDs thus should already be approved for access on the network," when research suggests that AM printers and other MFDs are in fact quite different. With a robust cybersecurity plan, the Marine Corps can shield against adversarial actions that would negate the gains already achieved with AM implementation into the Marine Corps.

C. WHAT SPECIFIC OPPORTUNITIES DOES AM PROVIDE THE MARINE CORPS THAT THEY ARE NOT PURSUING OR NOT PURSUING TO ITS FULLEST EXTENT?

AM has proven to effectively decrease maintenance time and costs. One such example is the 3DP of a helicopter helmet visor clip, which decreased the cost from $300 to $0.75 and the time from 9 months to 10 days (USD AT&L, 2017). However, AM can also provide printable systems to the warfighter where the acquisitions of the CAD file and printers are the cost and not the actual system. One such example of this AM capability is the fielding of the 3DP UAS system, which not only decreases the cost of the system from the \$200,000–\$250,000 range to about \$3,000 (USD[AT&L], 2017); it also allows for the on-site printing of the UAS without any requirement for traditional ordering, manufacturing, and shipment. This change in acquisitions will further decrease costs by not requiring the transport of the system and will also decrease the time to field these systems as the critical path is influenced by the printer speed, not the manufacturing and shipment of the system. In addition to increasing warfighter capabilities by fielding printers instead of systems, this change to the acquisitions of printers vice systems will shorten the acquisitions process to a more agile, responsive, and timely process (Schrand, 2016). However, AM offers two other unique opportunities to the Marine Corps. The first opportunity is increasing the flexibility for Marine Corps units responding to HADR operations. The second opportunity is to mitigate the threat that the Chinese WEZ presents to logistics operations inside the South China Sea.

1. HADR Operations

HADR operations are a key capability that the Marine Corps provides to the DOD and the nation's allies. All military services have HADR capabilities, but the Marine Corps' expeditionary roots make them ideal candidates to respond to natural disasters. With the addition of AM capabilities such as the TACFAB and XFAB, the Marine Corps can be even more responsive and impactful in responding to natural disasters. The tiered approach of AM capabilities to organizations further tailors capabilities to specific scenarios. The two likely tiers to respond to HADR events would be the operational and intermediate levels through the use of the TACFAB and XFAB, respectively. Unlike kinetic operations where security is paramount and the risk to force from adversarial actors is high, nonkinetic operations have decreased security concerns. Thus, with kinetic operations, only the TACFAB should be placed close to the forward edge of battle while the XFAB would be placed further back to increase security for that critical asset. However, if the Marine Corps were responding to a natural disaster today like it did in response to Super Typhoon Yolanda, both the organizational and intermediate level of AM could be placed at the point of need as the security concerns decreased. The ability to place both the TACFAB and

XFAB throughout the supply chain allows for further mobility, diminished supply line requirements, and longer operational endurance. For HADR operations, the lack of the XFAB's tactical mobility is not as significant, as it does offer strategic mobility to be transported throughout a host nation with the decrease in security risks. Thus, the change in security and mobility requirements during HADR operations allows the XFAB to be placed at major cities or towns that have been devastated, and the TACFAB and contact teams can disburse to outlying smaller towns and villages.

The current constraint facing the Marine Corps' HADR capabilities is not the TACFAB or XFAB concept, but the LulzBot TAZ 6 3D printer. As evident in the previously mentioned grading, the LulzBot scored poorly in withstanding harsh environments, having protected electronics, and having climate control mechanisms. It scored marginally in cost, modular design, and flexible power supply. All six of these categories are required during both kinetic and nonkinetic operations, but a flexible power supply is even more advantageous during HADR operations when traditional supply lines are destroyed and the transportation of fuel becomes either hindered or unavailable. The Kijenzi printer scored acceptable in five of these metrics and only marginal in one metric(i.e., the ablity to withstand harsh environments). Thus, the Marine Corps should focus efforts not on the concept of the TACFAB and XFAB but on what is the composition of the equipment within those systems.

2. AM Operations Inside the Chinese WEZ

The other unique opportunity AM provides the Marine Corps is its response to the Chinese ballistic missile threat against logistics activities occurring within the WEZ. As depicted in Figures 10 and 11, the Chinese possess an extensive and overlapping ballistic missile network. This network can threaten supply lines as far as San Diego, with the threat only increasing the closer those logistics activities move toward the South China Sea. If kinetic operations were to occur between the United States and China, U.S. forces operating in nations close to China—such as Vietnam, Philippines, Taiwan, South Korea, and Japan—could have their supply lines severely threatened. AM cannot mitigate the threat away completely for all classes of supply; however, it could provide certain classes of supply alternative means of obtaining the needed items and mitigate the risk.

The supply lines for Class I, III, and V cannot effectively be hardened with the use of AM. Even though the Marine Corps is making efforts to lighten ammunition with the use of AM (Athey, 2020), this ammunition production's objective is to decrease the weight of the ammunition, not provide ammunition production in a combat environment. Furthermore, LtGen Michael G. Dana highlighted in the *Marine Corps Installations & Logistics Roadmap, 2017* that Class I, III, and V are the primary classes of supply that need to be transported (DC I&L, 2017). Other avenues besides AM need to be pursued to harden those logistics activities while Marines operate in the South China Sea.

However, AM can provide logistics support to Marines operating within the WEZ for Classes VIII and IX. First, Class VIII and IX are generally more expensive than Class I, III, and V. Thus, ships transporting these high value items would be more appealing for the Chinese to strike with their own expensive ballistic missiles. However, if the item is printed on site, the Chinese do not have the ability to destroy the item in transit as the transportation requirement has been nearly removed. Second, the costs of transporting the items would be greatly reduced as the actual items being transported are raw materials and not the end-item. The threat to transportation is strikes against the raw materials, not the end-items. However, raw materials are less expensive and, therefore, less appealing as a target. Also, the raw materials can be shipped from various locations and countries and not the OEM, which is likely located within the continental United States. Therefore, transporting raw materials allows for greater concealment, as the raw materials are coming from multiple countries and locations instead of just a U.S. ship sailing from the continental United States.

D. DATA ANALYSIS CONCLUSION

The Marine Corps has taken great initial strides in implementing AM into the Marine Corps. The publication of MCO 4700.4 is a highly detailed document that provides initial guidance to all commanders and their Marines. The cultural shift has begun, and now is the time to harden the initial gains that AM has provided. One such activity will be to harden AM’s cybersecurity posture. However, AM also can provide unique opportunities to handle both nonkinetic operations, such as HADR operations, as well as kinetic operations of operating within the Chinese WEZ. Ultimately, the Marine Corps has achieved a programmatic approach to AM integration by decreasing cost and time while also increasing performance of warfighters capabilities.

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V. RECOMMENDATIONS

The primary objective of this research was to analyze the Marine Corps' current AM integration efforts. The research determined that, overall, the Marine Corps has effectively integrated AM technology within the force and predominantly through the publication of MCO 4700.4. This integration occurred in spite of the bureaucratic nature of the DOD (Schrand, 2016) and AM being a relatively new technology that is rapidly evolving. A secondary objective of this research was to determine unique risks to AM and whether the Marine Corps is adequately mitigating those risks. Furthermore, another objective was to determine unique opportunities that AM provides beyond the traditional maintenance and cost saving benefits. Even though new risks are presented with AM technology, and opportunities abound with such a versatile technology, the Marine Corps' cultural change regarding AM integration will help mitigate those risks and capture the benefits of various AM opportunities. This research provides these recommendations in the hopes of further revisions of MCO 4700.4. Finally, recommendations for further study are provided at the end of this chapter.

A. CYBERSECURITY RECOMMENDATIONS

Even though the Marine Corps has undergone a cultural change in AM adoption with the focus of a bottoms-up approach that focuses on training, risk tolerance instead of risk avoidance, and tiered application of AM equipment, the Marine Corps' primary AM risk remains cybersecurity. This research does not conclude that cybersecurity is not being considered; however, certain decisions suggest that cybersecurity risks are not being mitigated properly. The Marine Corps needs to engage DC I, Cyber Command, and other highly technical organizations to assist with cybersecurity efforts to help safeguard against adversarial action toward the benefits already achieved through AM integration. Two focus areas should be the connectivity of AM printers to the network and the security of the upcoming CAD file repository. If cybersecurity efforts are not taken, the Marine Corps assumes unnecessary risk toward a potential cybersecurity attack that can target the entire inventory of AM printers, the destruction and manipulation of CAD files, and other cybersecurity attacks.

B. RECOMMENDATIONS FOR AM OPPORTUNITIES

Beyond the cybersecurity risks, AM offers various opportunities to Marine Corps operational units. First, HADR operations can be more tailored and impactful to host nations while removing traditional burdens placed by the Marine Corps on the host nation, such as shipment of parts. Second, the Chinese WEZ presents a significant risk to logistics and resupply efforts in the South China Sea. AM cannot mitigate the entire risk but does offer certain classes of supply alternative means to acquire the necessary items, such as repair parts or consumable medical equipment. The Marine Corps must continue the risk-tolerant and bottoms-up approach to allow the junior Marines and junior officers to experiment and grow the AM integration. If this cultural tone is changed to be more top-down, the Marine Corps risks hindering or impeding further development from the junior ranks.

C. FURTHER STUDY RECOMMENDATIONS

As this research was limited to open-source information and by the inability to purchase printers, one area for further study presents itself regarding the Kijenzi and LulzBot printers. The discussion of these printers concludes that the Kijenzi printer is far superior to the LulzBot in both performance and cost parameters. However, the Kijenzi printer should not be blindly adopted to replace the LulzBot. Instead, a Kijenzi printer—along with other similar printers—should be purchased to thoroughly test the performance capabilities of all the printers before a cost, schedule, and performance decision is made. The LulzBot could still be the superior printer; however, it appears other printers exist that can perform beyond the LulzBot's capabilities at a significantly reduced price.

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